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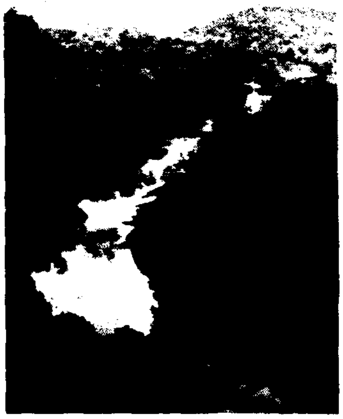

TECHNICAL REPORT EL-92-20

DISTRIBUTION AND ABUNDANCE OF FISH ABOVE HARTWELL DAM DURING A PERIOD OF ENTRAINMENT

by

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Following the entrainment of approximately 295,000 blueback herring (*Alosa aestivalis*) at Hartwell Dam, hydroacoustic surveys were performed in the dam forebay and in the lower portion of the corresponding reservoir to document the occurrence of fish in relation to the 34-m-deep water intakes of the dam's five hydroelectric generators. During the period 3-5 September 1990, a set of 15 acoustic surveys was performed in the dam forebay to monitor the abundance, distribution, and movement of fish during scheduled periods of power generation. A one-time acoustic survey to obtain similar information was also performed in the lower 7 km of Hartwell Reservoir.

Variable numbers of fish were detected in acoustic surveys of the dam forebay. Numbers of fish generally were low to moderate from 3 September through the afternoon of 4 September. Then, a large school of fish 28 to 40 m deep appeared near the dam, just west of the intake area. Over a 3-hr period, this school of fish grew in size and moved eastward to fill the area immediately in front of the water intakes. Echo integration results indicated that this school contained approximately 2.1 million fish at its largest size. The fish

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persisted in front of the water intakes from approximately 1745 hr on 4 September through the last forebay survey at approximately 1100 hr on 5 September.

Echo integration estimates from the reservoir survey indicated that approximately 3.1 million fish were present in the 28- to 40-m depth stratum of the lower 7 km of the reservoir. Outside the forebay region, densities of fish in the lower reservoir were greatest approximately 2 km above the dam, then gradually decreased until fish nearly disappeared at distances greater than 5 km from the dam. The gradual disappearance of fish in the 28- to 40-m depth zone generally paralleled the deteriorating dissolved oxygen concentrations that occurred within this depth stratum at increasing distances from the dam.

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Alosa aestivalis	Fish distribution
Anoxia	Hydroacoustics
Blueback herring	Hydroelectric
Dam	Hypolimnion
Entrainment	Hydropower
Fish	Reservoir
Fish abundance	

Contents

Preface

This study was sponsored by the US Army Engineer District (USAED), Savannah, under Intra-Army Reimbursable Services Order No. OP-R 9106, dated 25 October 1990. The work was performed by the Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES). Study manager for the USAED, Savannah, was Mr. Dave Coleman; technical supervisor was Mr. C. Michael Alexander.

The report was prepared by Messrs. Richard L. Kasul and Kenneth E. Conley of the Aquatic Habitat Group (AHG), Environmental Resources Division (ERD), EL. Analysis and interpretation of the acoustic data were greatly facilitated by observations and background information that were graciously provided by Mr. Joe Carroll of the Russell Limnological Laboratory-WES, Calhoun Falls, SC, and Mr. Alexander of the USAED, Savannah.

This work was conducted under the direct supervision of Dr. Edwin A. Theriot, Chief, AHG, and under the general supervision of Dr. Conrad J. Kirby, Chief, ERD; Dr. John Keeley, Assistant Chief, EL; and Dr. John Harrison, Chief, EL.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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1 Introduction

In late August and early September 1990, an estimated 370,000 blueback herring (*Alosa aestivalis*) were entrained at Hartwell Dam in conjunction with water releases for hydroelectric power generation. This total included approximately 40,000 herring entrained during power generation on 17-18 August, 110,000 on 27 August, 185,000 on 28 August, and 0 to 10,000 on other days during this period.

Following the large losses on 27-28 August, the US Army Engineer District, Savannah, expanded ongoing physical and biological investigations in the lower portion of Hartwell Reservoir to determine the cause of the herring entrainment. This report presents the results of one investigation consisting of fishery hydroacoustic surveys conducted in the Hartwell Dam forebay and the lower portion of Hartwell Reservoir during the period 3-5 September 1990.

The objectives of this study were to (a) document the distribution and movements of fish in the dam forebay during periods of water release, (b) determine the distribution of fish in the lower portion of Hartwell Reservoir, and (c) estimate the abundance of blueback herring in the dam forebay and the lower reservoir.

2 Study Area

Hartwell Lake is a Corps of Engineers reservoir created on the Savannah River in 1963 as part of a flood control and hydropower project. The lake was formed behind a 580-m-long concrete dam that, with earthen extensions, spans approximately 4.8 km across the Savannah River near Hartwell, GA. The reservoir extends approximately 18 km to the confluence of the Tugaloo and Seneca Rivers, 79 km up the Tugaloo, and 72 km up the Seneca. Approximately 22,500 ha of water surface is impounded behind the dam.

Sampling was conducted on the lower 7 km of the reservoir and in the dam forebay. This portion of the reservoir had a complex bottom topography that conformed to the hilly land features that existed prior to inundation. Much of the former forest that surrounded the original river channel stood as flooded timber. The lower reservoir attained a maximum depth of approximately 55 m in the original channel.

The forebay of Hartwell Dam was indicated by a floating line of connected warning buoys that enclosed an area in front of the water intakes of the dam's five hydroelectric generators. Water for electrical power generation was drawn into penstock openings in the dam that were located approximately 34 m below the surface. During the period of this study, the reservoir was stratified, and generators were turned with cool, low-oxygen water from the hypolimnion. As this study was being conducted, electric power generation was scheduled for weekday afternoons and evenings from about 1400 hr to 1900-2100 hr.

3 Methods

Field Surveys

A total of 15 mobile hydroacoustic surveys were performed in the dam forebay before, during, and after the period of water release for electric power generation. Seven of these surveys were performed from 1530-2030 hr on 3 September 1990 during a generation period extending from 1400-2100 hr. Seven surveys were also conducted on 4 September 1990 in conjunction with a generation period extending from 1400-1730 hr. The 4 September 1990 samples included a pregeneration survey at 1310 hr, four surveys during generation at hourly intervals from 1430-1701 hr, and two postgeneration surveys from 1744-1830 hr. On 5 September 1990, a pregeneration survey was begun at 1049 hr.

The forebay surveys were performed along fixed survey transects located inside the buoy line. A preliminary layout used on the first four surveys of 3 September 1990 consisted of a set of three to four transects extending the length of the concrete portion of the dam at successive distances from about 3 to 100 m from the dam face. The remaining 11 surveys consisted of a set of seven transects running perpendicular to the dam from the buoy line to within 2 to 3 m of the face of the dam (Figure 1). Three of these transects (D3, D4, and D5) were located directly in line with the water intakes for generating unit Nos. 1, 3, and 5. Two additional transects (D1 and D2) were located to the west of the intake area, and two others (D6 and D7) were located to the east of the intake area at floodgate Nos. 6 and 12.

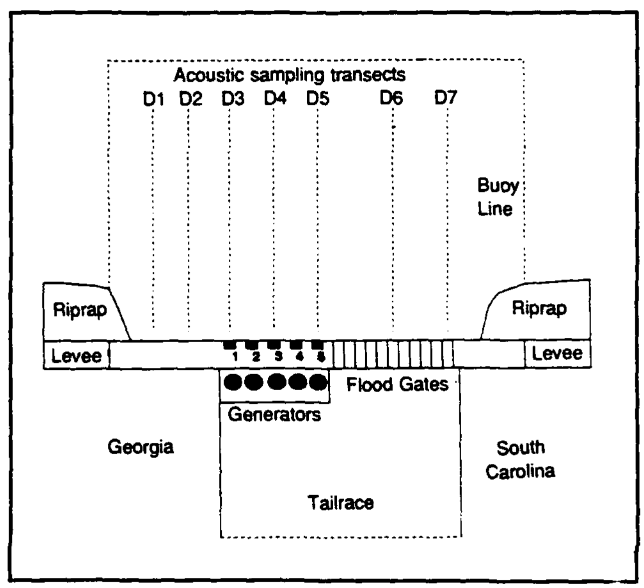

Figure 1. Schematic diagram of Hartwell Dam with acoustic transects D1-D7 in the forebay. Diagram is not shown to scale

The transect layout was changed from the preliminary to the final arrangement to reduce the incidence of sound reverberation from the face of the dam. With the preliminary arrangement, any fish within about 5 m of the dam were obscured by sound reflected from the dam. The reverberation intensity gradually decreased over a distance from approximately 5 to 20 m from the dam, but levels within this range were still high enough to affect quantitative fish measurements. With the final transect arrangement, acoustic interference was minimal even within 3 m of the dam (cf. Appendix A, p A2), and it did not affect quantitative analysis of fish detections.

While power generation was in progress, observers from the Savannah District monitored herring that passed through the turbines and into the dam tailrace. The observers could typically determine which of the five generating units were entraining fish, and they could provide a rough estimate of the numbers passing through the turbines at any particular time. The observers maintained radio contact with powerhouse operators so that, when necessary, generating units that were entraining fish could selectively shut down. An official estimate of the total number of herring entrained on any one day was made the next morning by biologists from State and Federal agencies who sampled or visually surveyed the dead and injured herring that accumulated in a riverine pool several kilometers downstream from the dam.

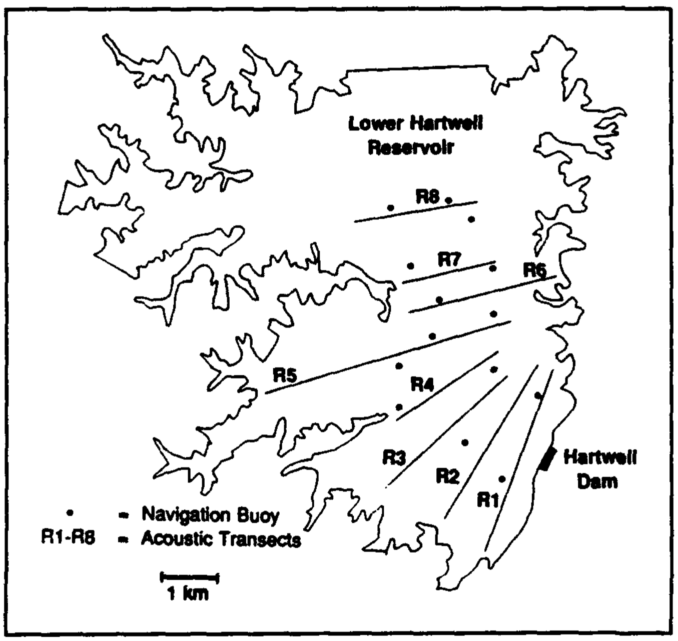

Figure 2. Acoustic survey area of lower Hartwell Reservoir. Survey transects are denoted as R1-R8

An acoustic survey of the lower 7 km of Hartwell Lake was performed on 5 September 1990. This survey consisted of eight transects approximately 2.5 km long that traversed the width of the reservoir (Figure 2). Transects began and ended nearshore in about 3 m of water so that each transect covered the deepwater area between the nearshore end points. Transects were spaced using buoy markers. Using starboard navigation buoys as a reference, transects began at buoy No. 2 about 0.5 km above the dam and ended near buoy No. 12 approximately 6.6 km above the dam.

Hydroacoustic data were collected with a Biosonics model 101 Echosounder and a 420-kHz

dual-beam transducer with a 6/15-deg nominal beam width. Narrow- and wide-beam echo signals were digitized with Sony Pulse Code Modulation and then recorded on the high-fidelity channels of Betamax video cassette tapes. The surveys were performed from a 7-m inboard/outboard boat that was modified for mobile acoustic sampling. The dual-beam transducer was mounted inside a stabilizing fin and towed from the front of the boat at a depth of about 0.66 m below the surface. The transducer was aimed downward for detection of acoustic scatterers between the near-surface and the bottom. The minimum effective detection distance, allowing for transducer depth and time varied gain (TVG) start-up distance, was approximately 2 m below the surface.

The echo sounder sampled at a rate of 5 sound pulses per second with a 0.4-msec pulse duration. Each transmission pulse sampled a cone-shaped volume that increased in size with increased range from the transducer. At a range of 30 m, for example, the narrow beam of the transducer sampled a nominal area approximately 3 m in diameter. The volume overlap from successive transmissions resulted in sampling of a continuous wedge-shaped volume of water on each survey transect that was narrowest near the surface and widest at the bottom.

Analysis

To verify system performance, two sets of echo collections were obtained during the study from a calibration sphere of known acoustic size. An evaluation of the dual-beam results from the calibration sphere data and a later factory inspection of the acoustic field equipment indicated that there was a reduced signal throughput in the wide-beam data channel resulting from a crack in the wide-channel carrier wire of the transducer cable. This caused the instrumentation to perform effectively as a single-beam acoustic system. As a result, the narrow channel data were analyzed with commonly employed methods for single-beam acoustic data collections. Performance of the narrow channel was evaluated using indirect target strength estimates as described by Johannesson and Mitson (1983) and the references cited therein.

Using factory calibration data and transducer directivity patterns from 8 September 1989, the mean target strength of the calibration sphere was calculated as -42.0 and -45.3 dB for the two sets of observations. Since measured values compared favorably with the -43 dB known size of this sphere, the narrow channel data were analyzed using 8 September 1989 calibration information.

A visual display of the echo detections recorded during each survey was reproduced on a thermal chart recorder. The echograms showed detections of fish, reservoir bottom, and inundated timber from narrow channel echo

returns that exceeded a minimum display threshold of 0.13 V (cf. Appendix A, p A2). The vertical and horizontal scales of these echograms were adjusted for presentation.

Fish abundance was estimated by a technique called echo integration which exploits the fact that integrated echo intensity is linearly related to fish density (Forbes and Nakken 1972). The technique was developed to estimate the abundance of schooling fish that cannot be resolved into individual acoustic targets. The integration process entailed sampling the voltage returns from fish echoes with a Biosonics model 121 Echo Integrator.

Voltage measurements associated with each integrator sample were squared and then summed for all fish detections occurring on a specified transect. Totals were separately recorded for each 1-m range interval from 2 to 55 m. At the end of a transect, the average echo intensity per transmission pulse was calculated for each range class. The result was then multiplied by a range-dependent B constant to convert from the 40 Log (R) TVG amplification used for data collection to the 20 Log (R) TVG amplification that is used in echo integration to compensate for one-way spreading loss. The resulting sum-of-squares voltages V_x for range classes $x = 2,3...55$ were estimates of fish biomass expressed in units of V^2.

Values of V_x were multiplied by an integrator scaling constant A to yield estimates of fish abundance in fish per cubic meter. These were then added across appropriate depth strata to obtain fish per square meter of surface area. The A constant was calculated as

$$A = \frac{1}{\pi \tau c p_o^2 g_T^2 b_{av}^2(\theta)\, \sigma_{bs}} \qquad \frac{fish}{V^2}\,\mathrm{m}^3$$

where

π = 3.1316

τ = 0.4×10^{-4} sec pulse width

c = 1,485 m/sec, sound velocity in water

p_o^2 = $(9.33 \times 10^{10})^2$, transmitted pressure level squared

g_T^2 = $(1.30 \times 10^{-8})^2$, squared through system gain for narrow channel

$b_{av}^2(\theta)$ = 0.9689×10^{-3}, average beam factor pattern for narrow beam

σ_{bs} = 0.1175×10^{-4}, mean area backscatter per fish

The mean acoustic size of fish in decibels and equivalently the mean area backscatter of fish for the integration A constant were determined using indirect target strength methods from data collected on the narrow-beam

transducer element (Johannesson and Mitson 1983). The validity of the indirect target strength estimates was contingent upon the fairly reasonable assumption that fish encounters were uniformly distributed across the face of the transducer during sampling.

4 Results and Discussion

Vertical Distribution of Fish

Echograms showed that most fish in the forebay and in the lower portion of the reservoir occurred in the 2- to 15-m or in the 28- to 40-m depth strata. Water quality profile data collected as part of another investigation indicated that the upper zone corresponded to the warm (>23 ^{o}C), oxygenated (4 to 8 mg/L) epilimnion of a stratified reservoir and the lower zone corresponded to a 28- to 40-m-deep layer within the hypolimnion with slightly elevated levels of dissolved oxygen.[1] Within the 28- to 40-m stratum, dissolved oxygen slightly exceeded 1.5 mg/L against background levels of less than 0.5 mg/L elsewhere in the hypolimnion. Echograms from several forebay and reservoir surveys showed a well-defined layer in fish occurring in this region of the hypolimnion.

Entrainment risk appeared to be greatest for fish in the 28- to 40-m depth stratum because they occurred at about the same depth as the 34-m-deep generator intakes. There were three reasons to suspect that these fish were primarily blueback herring. First, the entrained fish that entered the penstocks at this depth were mostly herring. Second, herring were caught at this depth in a complementary netting study conducted in the Hartwell forebay. Third, acoustic echograms showed that fish occurring at this depth exhibited schooling behavior like that of blueback herring.

Acoustic Size

Of fish detections in the forebay and reservoir surveys, only 66 fish from the 28- to 40-m depth zone were individually isolated for acoustic size determination. This number represented those individuals that were

1 C. M. Alexander et al. 1991. Entrainment of blueback herring (*Alosa aestivalis*) at Hartwell Dam, South Carolina and Georgia: A case study. Natural Resource Management Center, Richard B. Russell Lake. Savannah, GA: US Army Engineer District, Savannah.

separated from other fish in their school by a distance sufficiently large to permit acoustic detection as single fish targets. The low number of detections of individual fish was indicative of the high degree of schooling of fish in the 28- to 40-m depth zone. The mean acoustic size of these fish was approximately -49.3 dB.

In comparison, the mean acoustic size of blueback herring detected in nighttime surveys in the tailrace of Richard B. Russell Dam was approximately -41 to -47 dB, and the corresponding mean length of blueback herring caught there by purse seine was 14 to 16 cm (Schreiner 1990). The somewhat smaller acoustic size of suspected blueback herring at Hartwell may be reasonably attributed to a deeper detection depth at Hartwell (28 to 40 m) than at Richard B. Russell (1 to 4 m).

More than 90 percent of reflected energy from an ensonified fish typically originates from the swim bladder (Johannesson and Mitson 1983). Herring obtain swim bladder gases while at the surface, and they cannot absorb additional gas while submerged (Brawn 1962). As herring descend from the water surface, the swim bladder is compressed into a smaller surface area (Bone and Marshall 1982), which in turn presents a smaller acoustic target. As a result, the same individual fish can have a smaller acoustic size at a greater depth. For example, a 50-percent reduction in the surface area of the swim bladder resulting from depth compression could result in a target strength decrease of approximately 6 dB. The effect of gas compression on the swim bladder was observed in blueback herring that had been entrained at Hartwell. Biologists who observed these fish noted that some of them sustained apparent injury caused by a rapid expansion of the swim bladder when the fish left the forebay at a depth of approximately 34 m and passed into tailrace waters near the surface.

Forebay Surveys

The abundance and distribution of fish acoustically observed in the 28- to 40-m depth layer varied widely in the 15 forebay surveys conducted on 3-5 September 1990. A descriptive summary of observations on fish distribution and movement in the forebay area is presented in Table 1, and estimates of fish density in the forebay are presented in Figure 3.

An estimated 5,000 blueback herring passed through the generators on 3 September 1990. Many of these fish were entrained during the late afternoon during a period when acoustic surveys were conducted at approximately hourly intervals. However, no fish were acoustically detected near the water intakes at any time on 3 September 1990. Apparently the fish present in the intake area had escaped acoustic detection. These may have been relatively small groups of fish that passed along the face of the dam. Such fish would have a low probability of detection because the transects

Table 1
Summary of Acoustic Fish Surveys Conducted in Hartwell Dam Forebay, 3-5 September 1990

Survey Time, hr	Observations[1]
Monday, 3 September 1990	
1530	No significant fish detections in forebay.
1601	No significant fish detections in forebay.
1635	No significant fish detections in forebay.
1702	No significant fish detections in forebay.
1810	No significant fish detections in forebay.
1847	School of fish detected on transects D1 and D2 where sloping nearshore bottom passes through 34-m depth zone. No significant fish detections elsewhere in forebay.
2034	After dark. Fish school present on transects D1 and D2 during the previous survey is gone. Small schools are now scattered throughout the forebay.
Tuesday, 4 September 1990	
1310	One hour before generation. Numerous small schools of fish detected throughout the forebay. Scattered schools occur within 40 m of intakes for generating units Nos. 1 and 3.
1430	Survey started immediately after last of five units brought online. Fish in forebay area greatly reduced from previous survey . Small schools appear on transects D1 and D2 where sloping bottom passes 34-m depth zone. A few fish present within 40 m of unit No. 1.
1525[2]	Greater number of fish schools in forebay area than detected in the previous survey. No significant fish detections near the penstocks.
1613[2]	Similar to previous survey.
1701[2]	Large school of fish appeared on transects D1 and D2. Only a few scattered fish detected elsewhere in forebay.
1744[2]	School of fish on transects D1 and D2 greatly increased in size and now extends across transect D3 in front of the intake for unit No. 1. Scattered schools of fish also reappear elsewhere in forebay.
1830[2]	Fish move eastward to fill area in front of all five generator intakes. Abundance is increased over previous survey.
Wednesday, 5 September 1990	
1049[2]	Pregeneration. School of fish persists in front of penstocks but appears to be considerably smaller than observed during the survey of 1830 hr on 4 September.

[1] Observations denote visual echogram interpretations of fish abundance and distribution in the 28- to 40-m depth strata where blueback herring are thought to occur.
[2] Survey echograms shown in Appendix A.

that were run perpendicular to the dam to minimize acoustic interference provided a fairly low level of acoustic coverage along the face of the dam.

On 4 September 1990 a variable number of small to moderate-sized schools were found in the 28- to 40-m-deep region of the forebay between 1310 and 1635 hr. At 1701 hr, a large school of fish appeared near the dam on transects D1 and D2 at the point where armored shoreline passed through the 34-m depth zone. At 1744 hr, the school shifted slightly

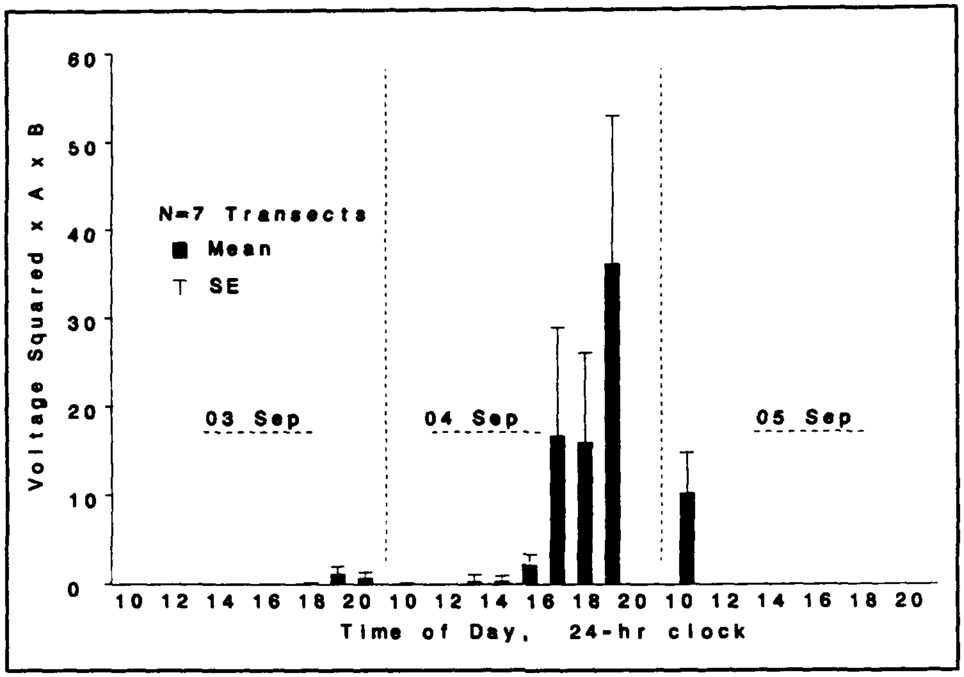

Figure 3. Acoustic integration estimates of mean fish biomass in the Hartwell Dam forebay in 11 surveys performed on 3-5 September 1990. Integrator biomass units correspond to fish per square meter over the 28- to 40-m depth stratum

eastward to fill the area in front of the intake for generator No. 1. By 1830 hr, this school had increased in size and shifted farther eastward to completely cover the intake area in front of all five penstocks. At 1049 hr on the morning of 5 September 1990, this school was still present in front of the penstocks though it was reduced in size from the previous night. The buildup and movements of this school from 1525 hr on 4 September to 1049 hr on 5 September are shown in Figure 4. A complete set of survey echograms for this same period is provided in Appendix A.

Within the large school of fish that moved into the penstock area, maximum densities of fish reached 100 per square meter of forebay surface area within a water layer that was approximately 6 m deep. This density would correspond to a mean three-dimensional spacing of approximately 40 cm between fish. Based on acoustic integration results, the large school that moved in front of the penstocks at 1830 hr contained an estimated 2.1 million fish. At 1049 hr the next day, approximately 0.7 million fish still remained in this area.

The large numbers of fish that moved into the intake area on 4 September 1990 provided a means of assessing the effectiveness of the entrainment monitoring and response system. On this day, powerhouse operators began to shut down the generators at approximately 1730 hr, just as the leading front of the school was beginning to move in front of generating unit No. 1. By this time approximately 10,000 herring had been entrained during the

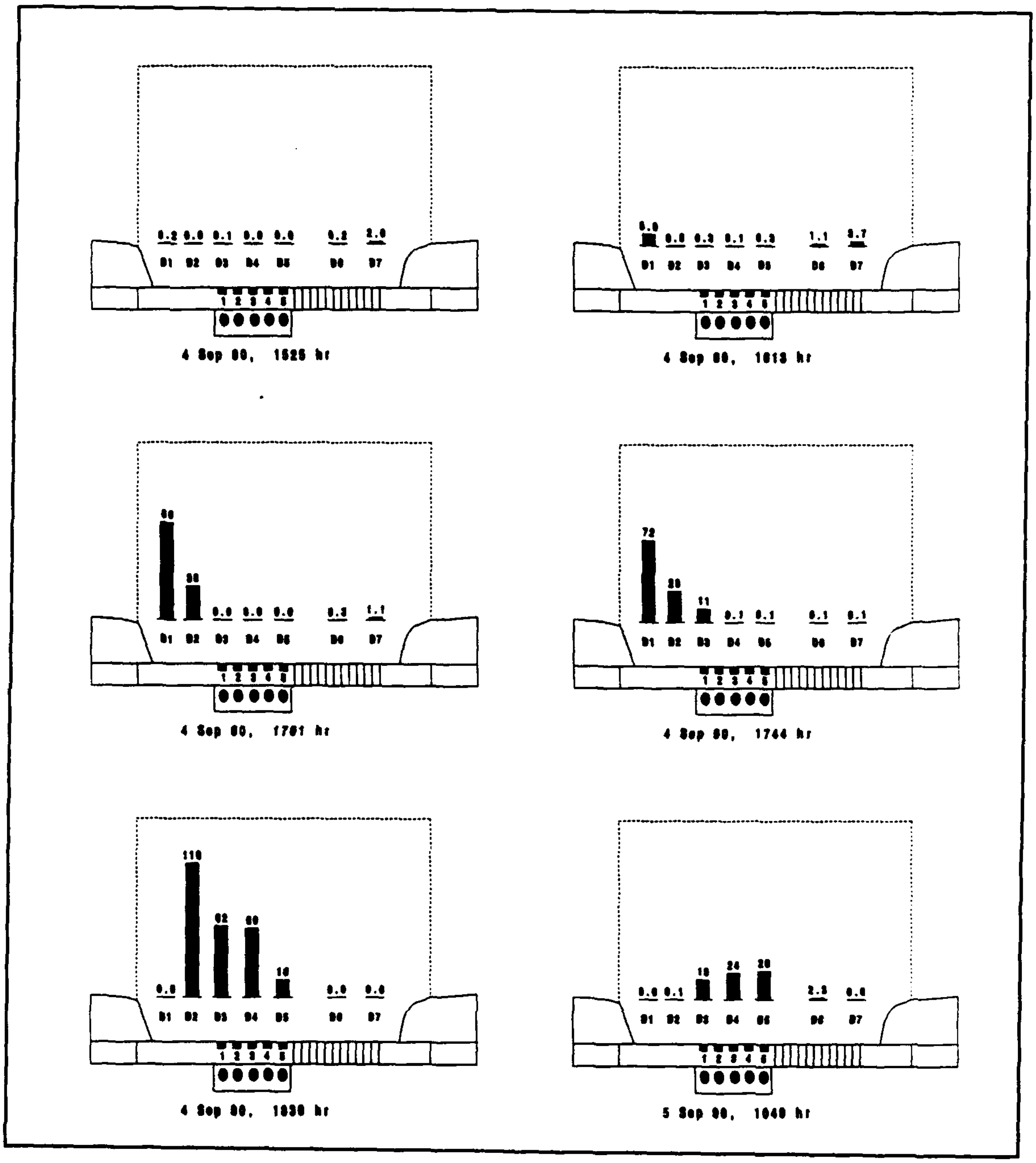

Figure 4. Acoustic integration estimates of fish biomass for the individual transects of six acoustic surveys performed in Hartwell Dam forebay on 4-5 September 1990. Integrator biomass units correspond to fish per square meter over the 28- to 40-m depth stratum

day. The early shutdown of the generators may have prevented substantial entrainment like that which occurred on 27 and 28 August when 110,000 and 185,000 herring were entrained, respectively. The decision to shut down generation at this time was based solely on reports from the entrainment observers. Because there was no radio contact at this time with the acoustic survey personnel, powerhouse operators had no knowledge of the large school of fish that was moving into the penstock area. In this instance, the

observer and decision system in place at Hartwell Dam appears to have effectively minimized entrainment losses.

Reservoir Survey

Echograms from the reservoir survey showed a concentration of fish in a stratum approximately 28 to 40 m deep that occurred throughout most of the lower 5 km of the reservoir (Appendix A). Fish were present in this layer almost everywhere the water depth exceeded about 28 m. Integrator estimates of fish density in this layer varied from 0.00 to 0.46 fish/m^2 on the eight survey transects of the lower reservoir. There was a trend in which density increased from 0.08/m^2 on transect R1 to 0.46/m^2 on transect R3, then decreased until fish nearly disappeared on transect R8, approximately 6.6 km above the dam (Figure 5). The gradual disappearance of the fish in the upper portion of the survey areas was consistent with the dissipation of the water layer containing elevated levels of dissolved oxygen that extended for approximately 4 km above the dam.

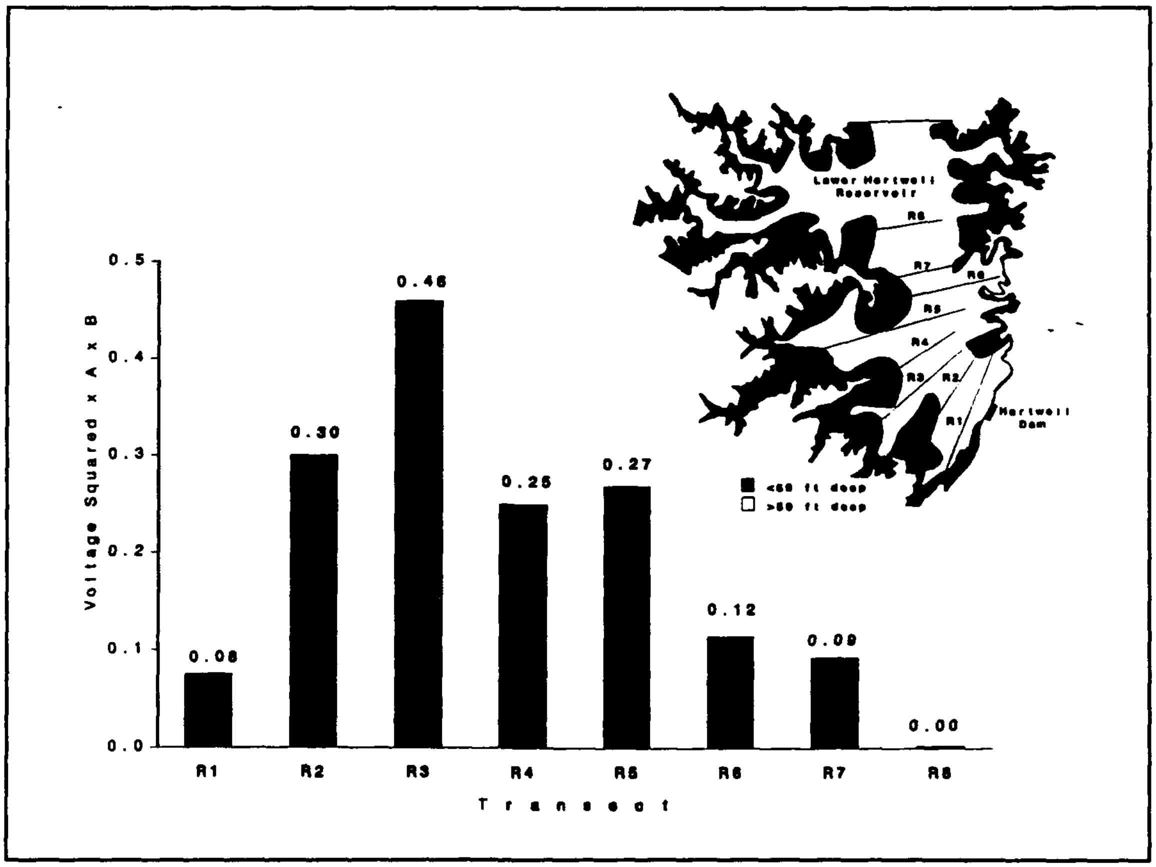

Figure 5. Acoustic integration estimates of fish biomass for individual transects of an acoustic survey performed in Hartwell Dam forebay on 5 September 1990. Integrator biomass units correspond to fish per square meter over the 28- to 40-m depth stratum

The mean density of fish in the lower reservoir was 0.22 ± 0.05 (SE) per square meter. This density multiplied by the surface area of the deep-water portion of the lower reservoir, approximately 1,550 ha, provides an estimate of 3.1 million ± 1.6 million (95-percent confidence limits) fish in the 28- to 40-m depth zone of the lower reservoir. This estimate does not appear to be excessive for a schooling forage fish. In 13,000-ha Lake Norman in North Carolina, for example, threadfin shad have been estimated to exceed 300 million (Siler 1986).

Comparison of Forebay and Reservoir

Echograms and density estimates suggested that the distribution of 28- to 40-m-deep fish was different in forebay and lower reservoir areas. In the forebay, fish were found primarily in distinct schools ranging in size from small to large with densities exceeding 100/sq m in some instances (Figure 4). These schools appeared to be quite mobile and, as indicated by comparison of surveys conducted before, during, and after generation on 4 September, their distribution and movements changed appreciably during the generation period. Abundance estimates indicated that nearly as many fish may have occurred in the forebay as in the much larger area of the lower reservoir.

In contrast, fish occurring in the lower portion of Hartwell Reservoir were found in much lower densities (less than 0.25/sq m), but they appeared to be more uniformly distributed over a much larger area. The decreasing densities and gradual disappearance of fish that began approximately 4 km above the dam may have been in response to stresses associated with deteriorating dissolved oxygen levels.

5 Conclusions

The approximately 370,000 blueback herring entrained in late August and early September 1990 were only a modest proportion of the herring stocks present in the forebay and in the lower portion of Hartwell Reservoir. The potential stock remaining at the end of this period included approximately 3 million fish in the lower 5 km of the reservoir, and possibly more if forebay estimates can be added to this total.

Major entrainment losses probably occur when a large school of herring assembles in front of the penstocks and stays for many hours of power generation. The nearly 300,000 herring entrained on 27-28 August 1990 were probably associated with a large school of herring much like the one containing approximately 2 million fish that appeared in front of the penstocks on 4 September 1990. By terminating power generation as these fish began to appear at the penstocks, dam operators may have prevented a major entrainment episode. This experience indicates that close monitoring of entrainment combined with responsive management of power generation may prevent major entrainment losses.

Until a more permanent solution is developed, entrainment losses could be reduced if high-risk periods were identified with sufficient lead-time to permit mobilization of entrainment monitoring procedures. Since herring entrainment occurs only in some years and appears to be influenced by measurable water quality conditions, it may be possible to develop a framework for predicting which years carry a high risk for entrainment. A better understanding of the conditions that lead to entrainment, how and when those conditions arise in the reservoir, and how fish respond to them may provide a basis for successful prediction of annual entrainment risk.

6 Summary

In response to the entrainment of approximately 295,000 blueback herring (*Alosa aestivalis*) that occurred in conjunction with hydroelectric power generation at Hartwell Dam on 27-28 August 1990, the US Army Engineer District, Savannah, expanded ongoing biological and physical studies in the Hartwell Dam forebay and the lower portion of Hartwell Reservoir. One of the additional studies involved 15 fishery acoustic surveys that were performed in the dam forebay on 3-5 September 1990 to monitor fish abundance, distribution, and movements near the intake area during scheduled periods of power generation. The investigation also included a background acoustic survey of the lower 7 km of the reservoir performed on 5 September 1990.

In both forebay and reservoir surveys, most fish were acoustically detected in 2- to 15-m and 28- to 40-m depth strata. The upper zone corresponded to the epilimnion of the stratified reservoir, and the lower zone corresponded with a layer of water within the hypolimnion containing slightly elevated levels of dissolved oxygen. The acoustic studies focused on fish detections in the lower depth stratum because this region occurred at the same depth as the water intakes for the hydroelectric generators and because a complementary study had identified blueback herring as a principal species of fish occurring there.

Detections of fish in the forebay ranged from none to moderate from 3 September through the afternoon of 4 September. Then, late in the afternoon on 4 September, a large school of fish occurring 28 to 40 m deep appeared near the dam to the west of the intake area. In the evening and early nighttime hours, this school of fish moved eastward to fill the area in front of the water intakes and, as it did so, attained a size of approximately 2.1 million fish. Major entrainment losses were possibly avoided on 4 September by successful implementation of a decision system that allowed powerhouse operators to shut down the generators before substantial numbers of fish appeared in front of the intakes.

In the forebay surveys, fish located 28 to 40 m deep typically occurred in mobile schools of high density that ranged in size from small to quite large. In the reservoir, the fish in this depth stratum occurred in schools of lower density and were more uniformly distributed throughout the

open-water area. An estimated 3.1 million fish were present in the 28- to 40-m depth stratum of the lower reservoir in an area that extended for about 5 km above the dam.

Circumstantial evidence indicates that abundance, distribution, and movement of 28- to 40-m-deep fish in the forebay and in the lower reservoir were influenced by water quality conditions. These conditions, particularly the water layer in the hypolimnion containing elevated levels of dissolved oxygen, allowed fish to occur at the same level as the water intakes, and may have placed them at risk for entrainment for as long as these conditions persisted.

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Appendix A Echograms from Selected Surveys

Note: Locations of acoustic transects were as follows:

Hartwell Dam Forebay (Figures A1-A7)

Transects 1-2, west side of penstocks (Georgia)
Transects 3-5, in front of penstocks of units 1, 3, and 5
Transects 6-7, east side of penstocks (South Carolina)

Hartwell Reservoir (Figure A8) - (approximate distance above dam)

Transect 1, 0.8 km
Transect 2, 1.6 km
Transect 3, 2.5 km
Transect 4, 3.2 km
Transect 5, 3.9 km
Transect 6, 4.6 km
Transect 7, 5.2 km
Transect 8, 6.6 km

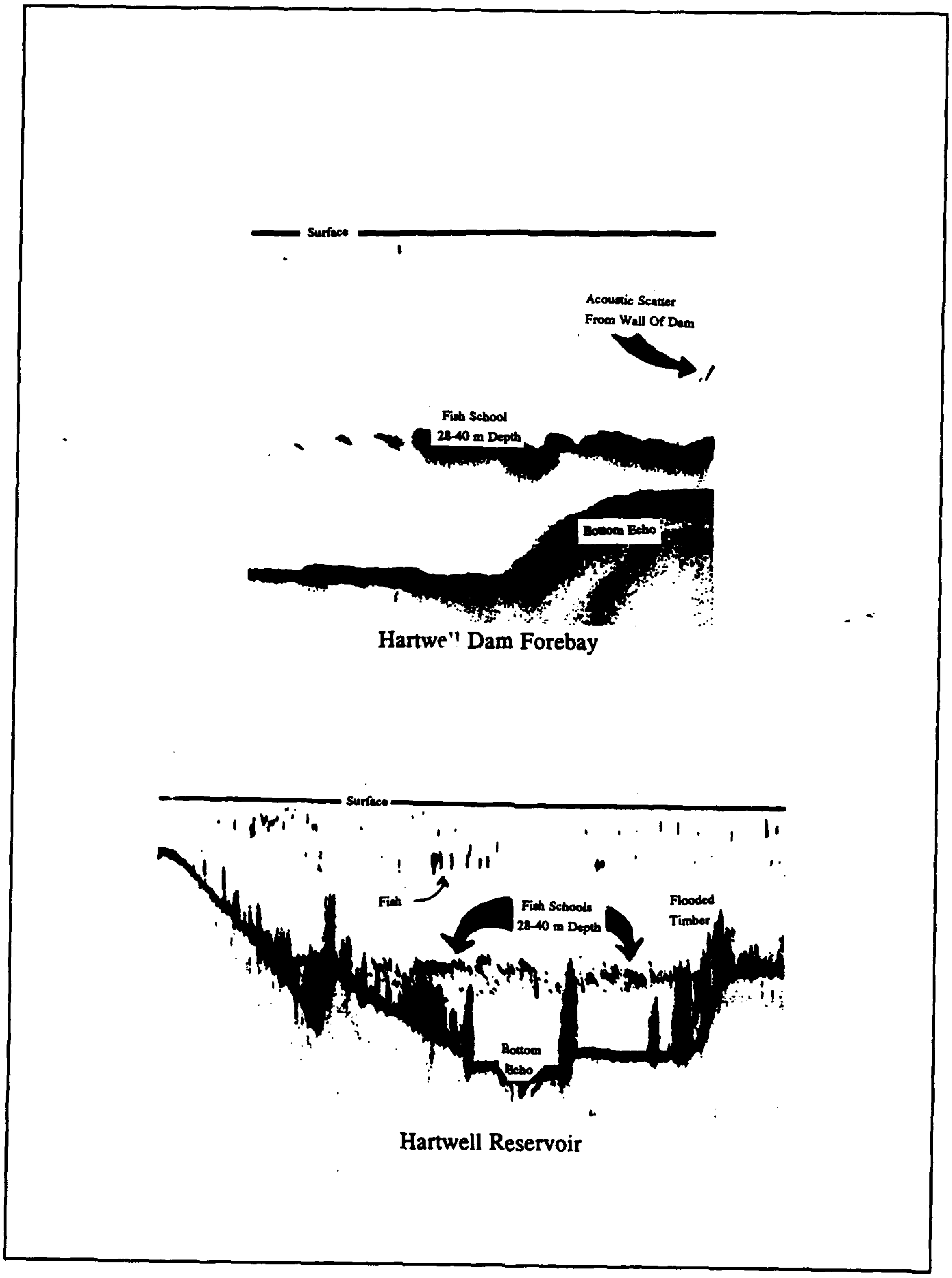

Figure A1. Annotated examples of echograms

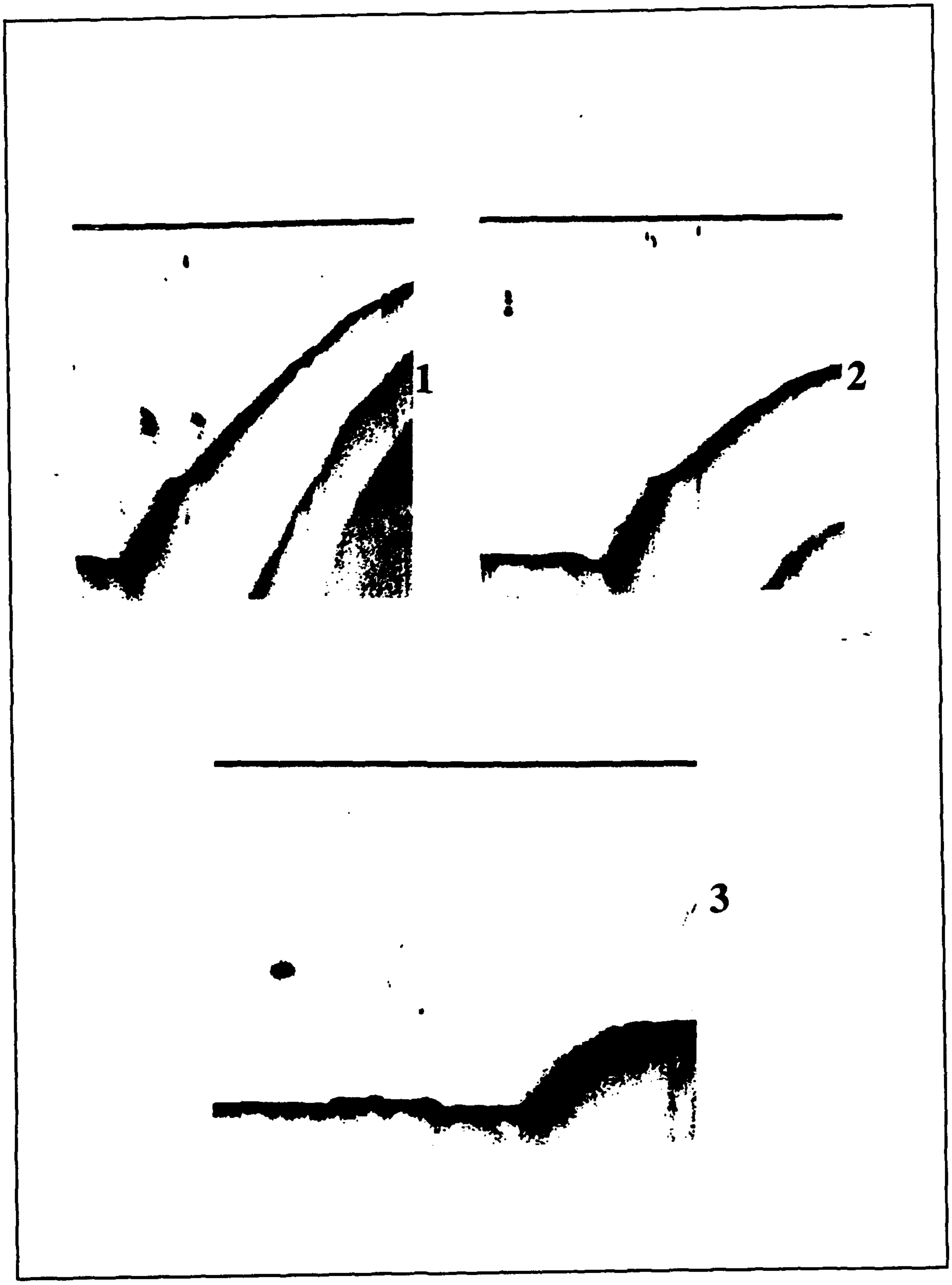

Figure A2. Hartwell Dam forebay, 4 Sep 90, 1525 hr (buoy line on left; face of dam on right) (Sheet 1 of 3)

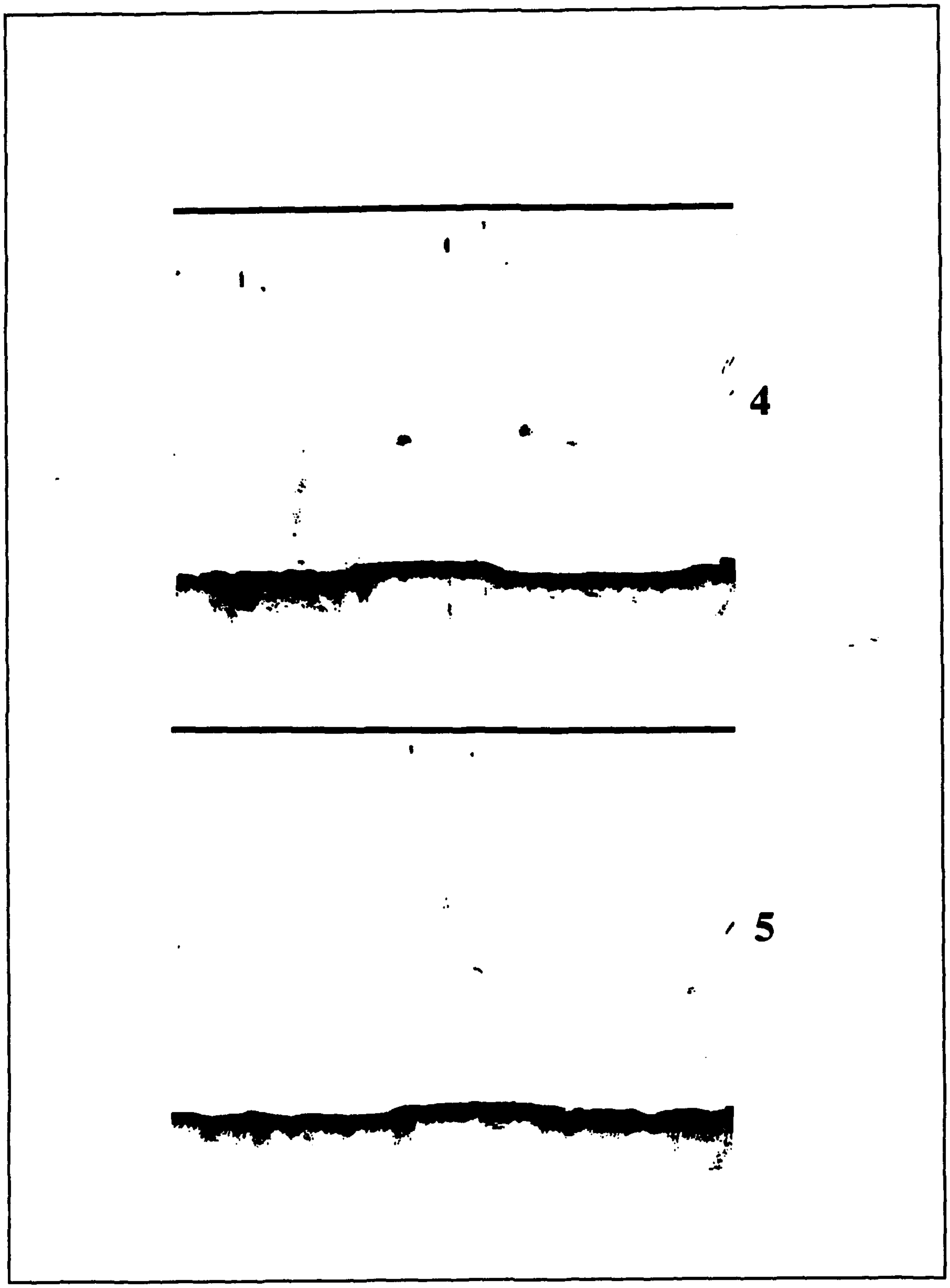

Figure A2. (Sheet 2 of 3)

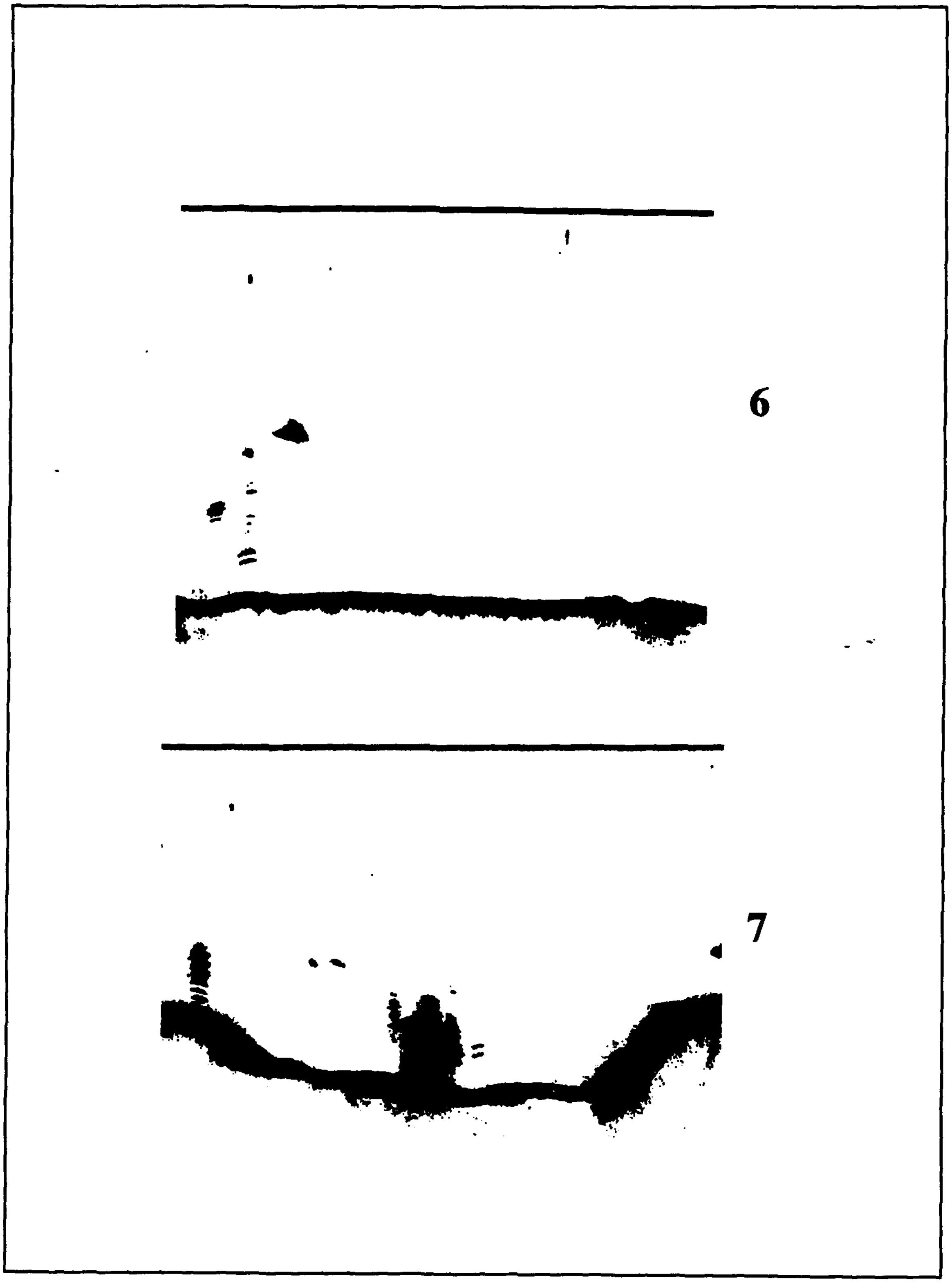

Figure A2. (Sheet 3 of 3)

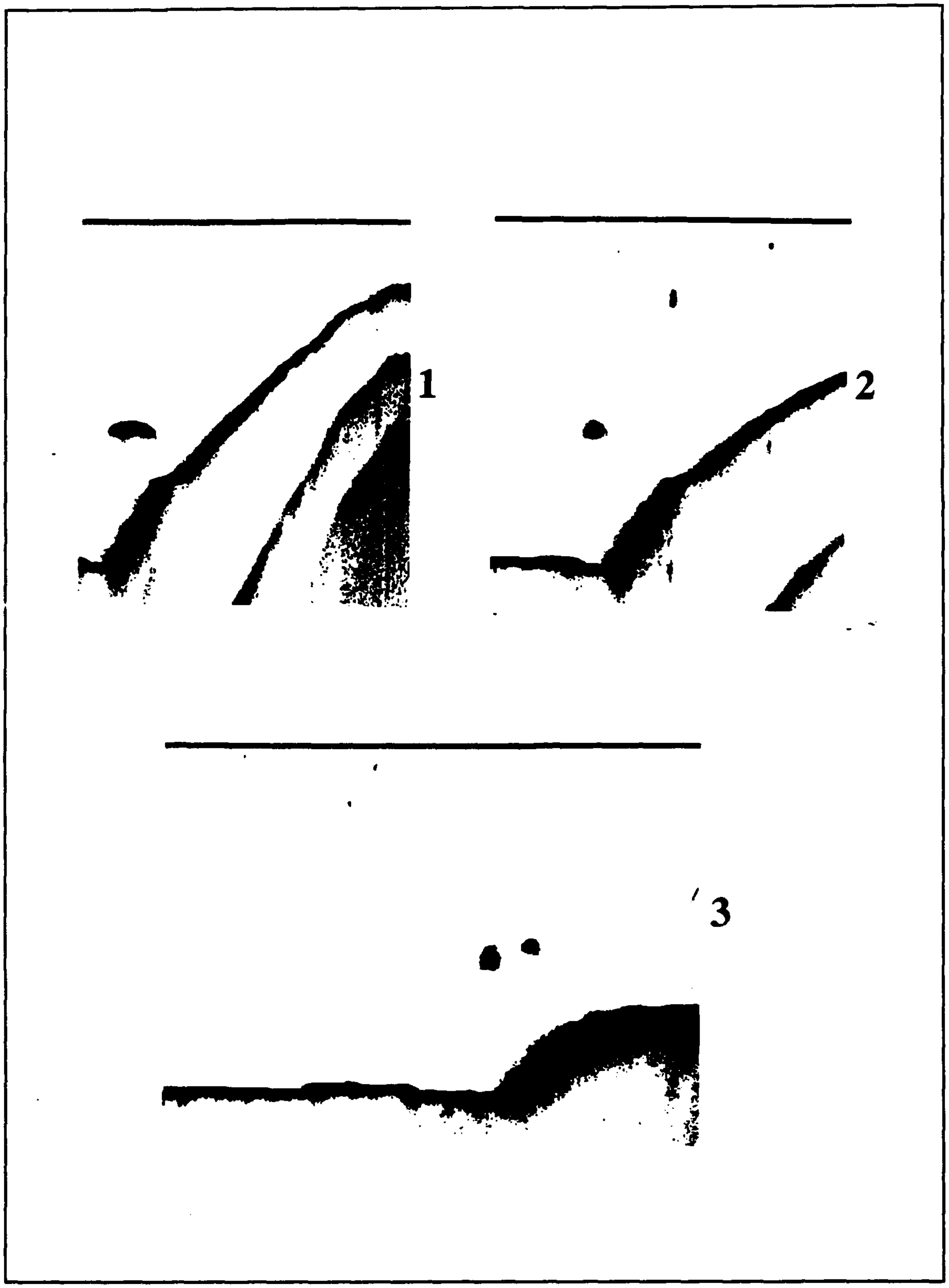

Figure A3. Hartwell Dam forebay, 4 Sep 90, 1613 hr (buoy line on left; face of dam on right) (Sheet 1 of 3)

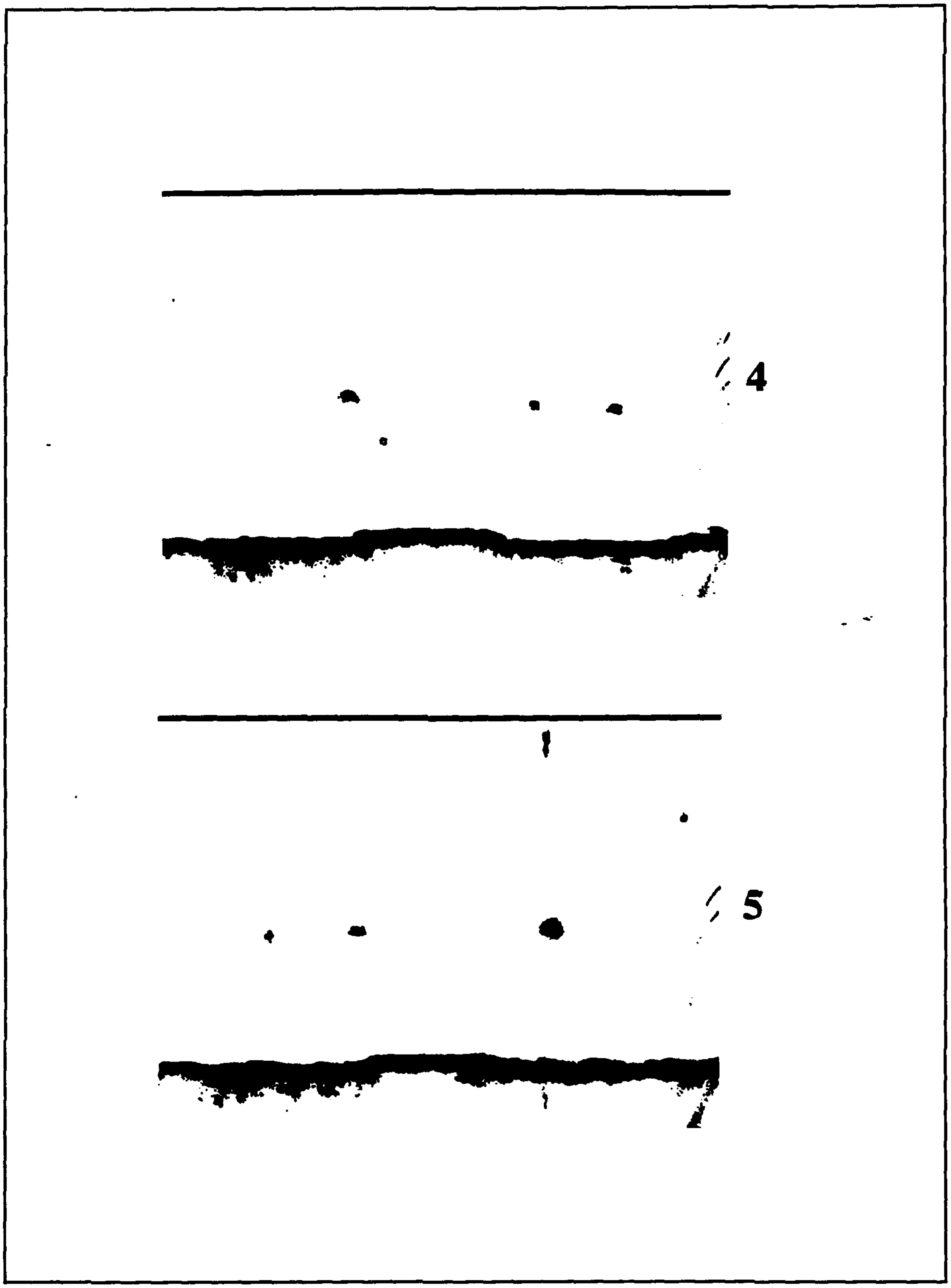

Figure A3. (Sheet 2 of 3)

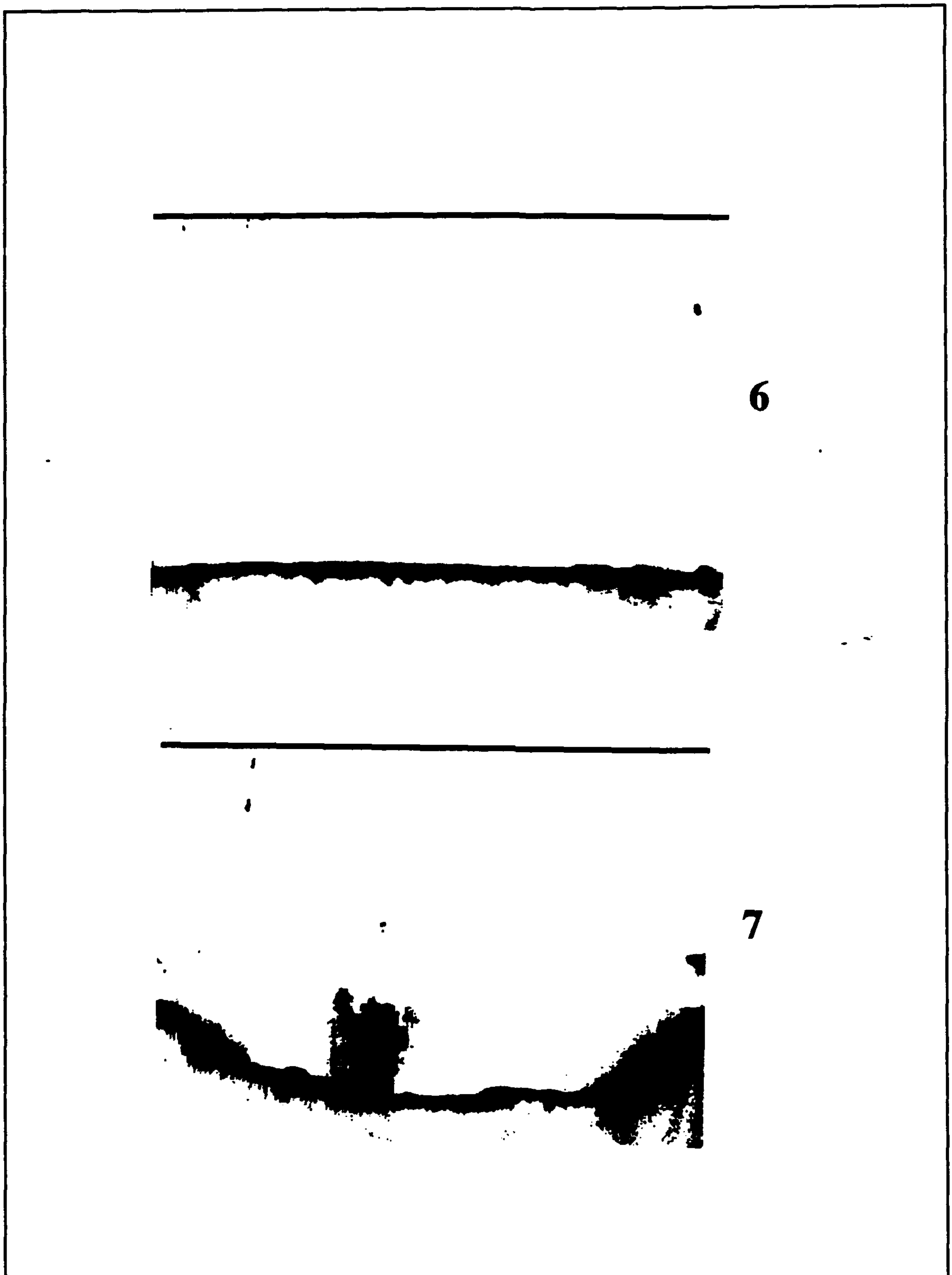

Figure A3. (Sheet 3 of 3)

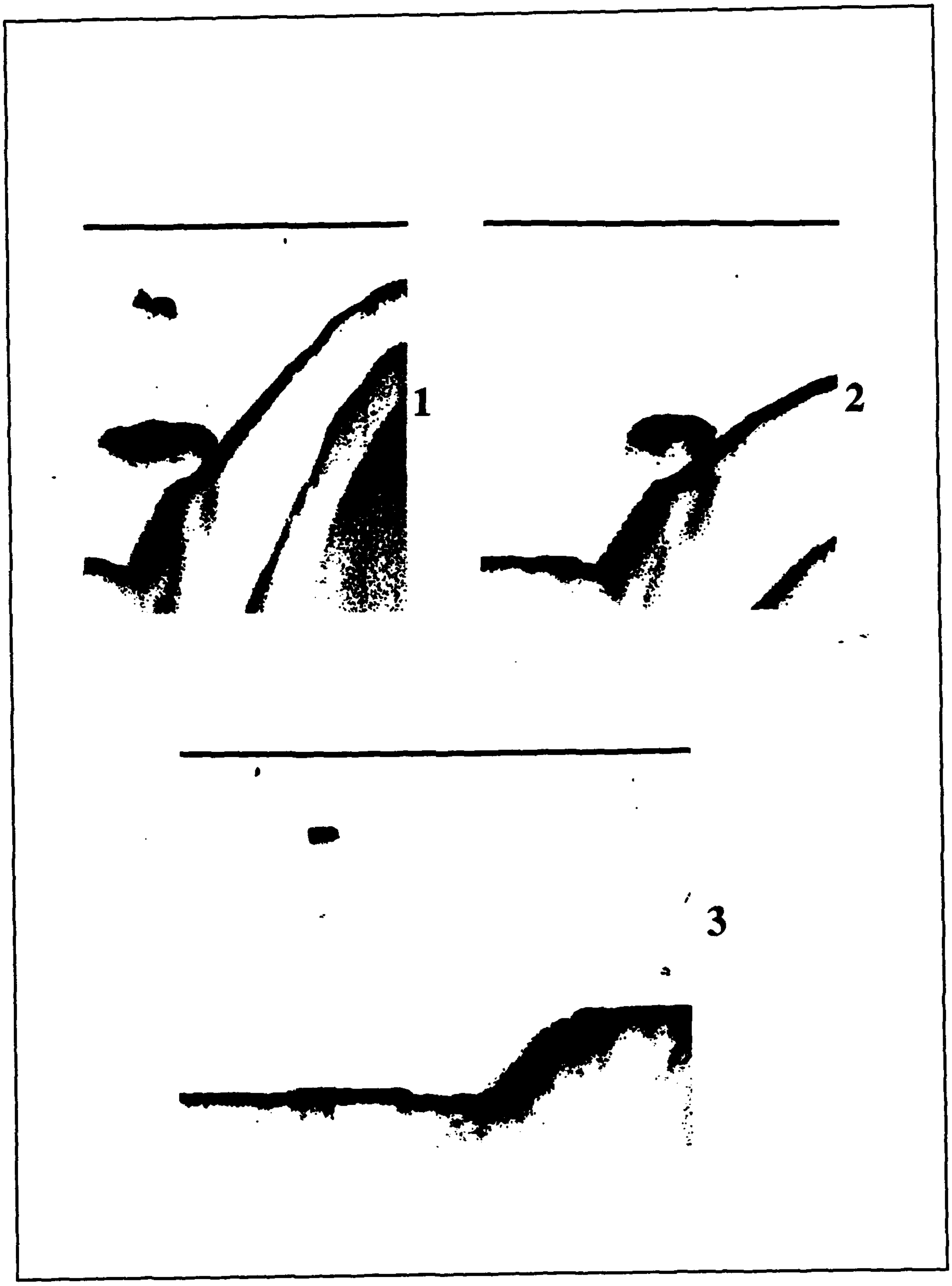

Figure A4. Hartwell Dam forebay, 4 Sep 90, 1701 hr (buoy line on left; face of dam on right) (Sheet 1 of 3)

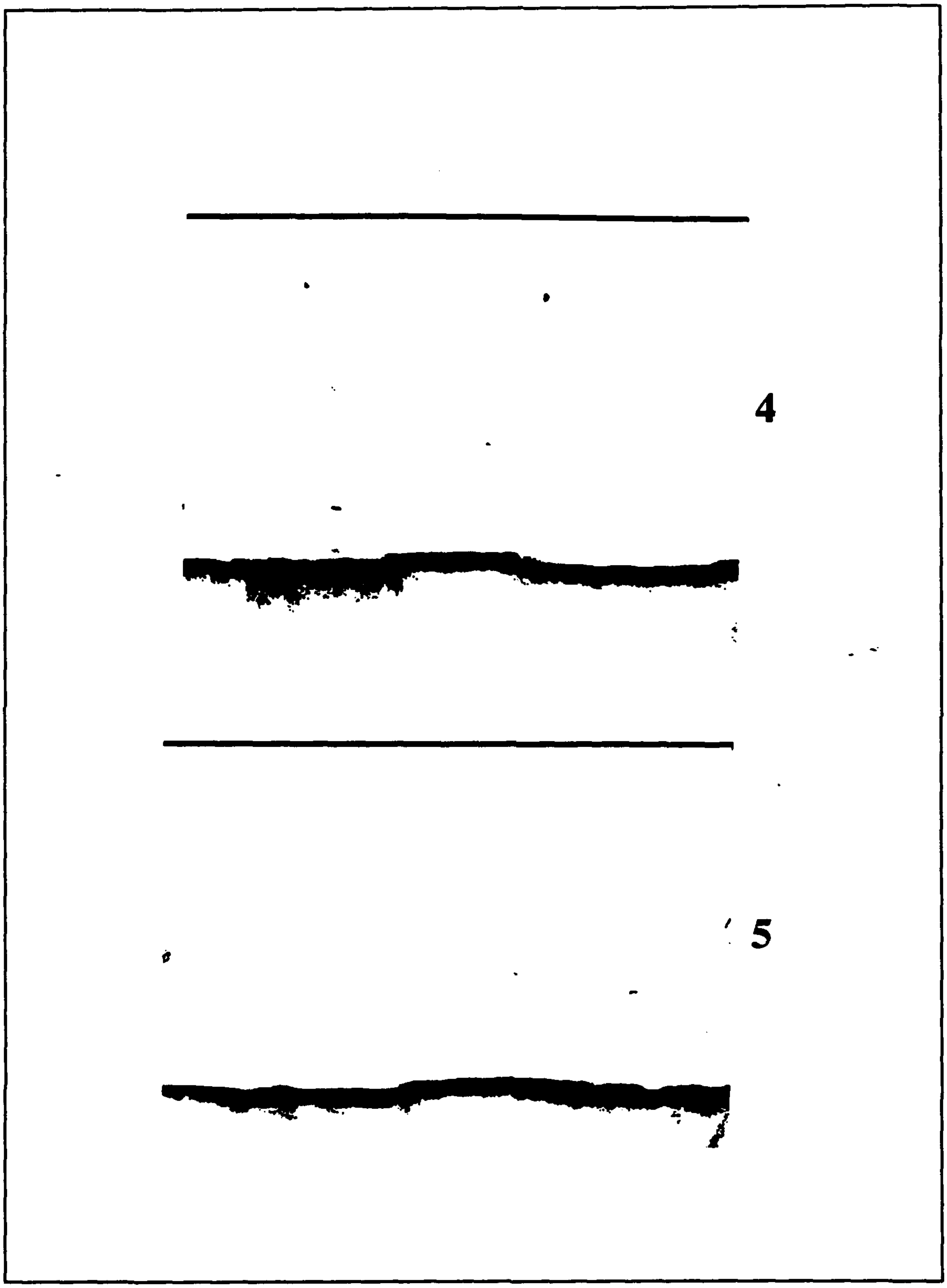

Figure A4. (Sheet 2 of 3)

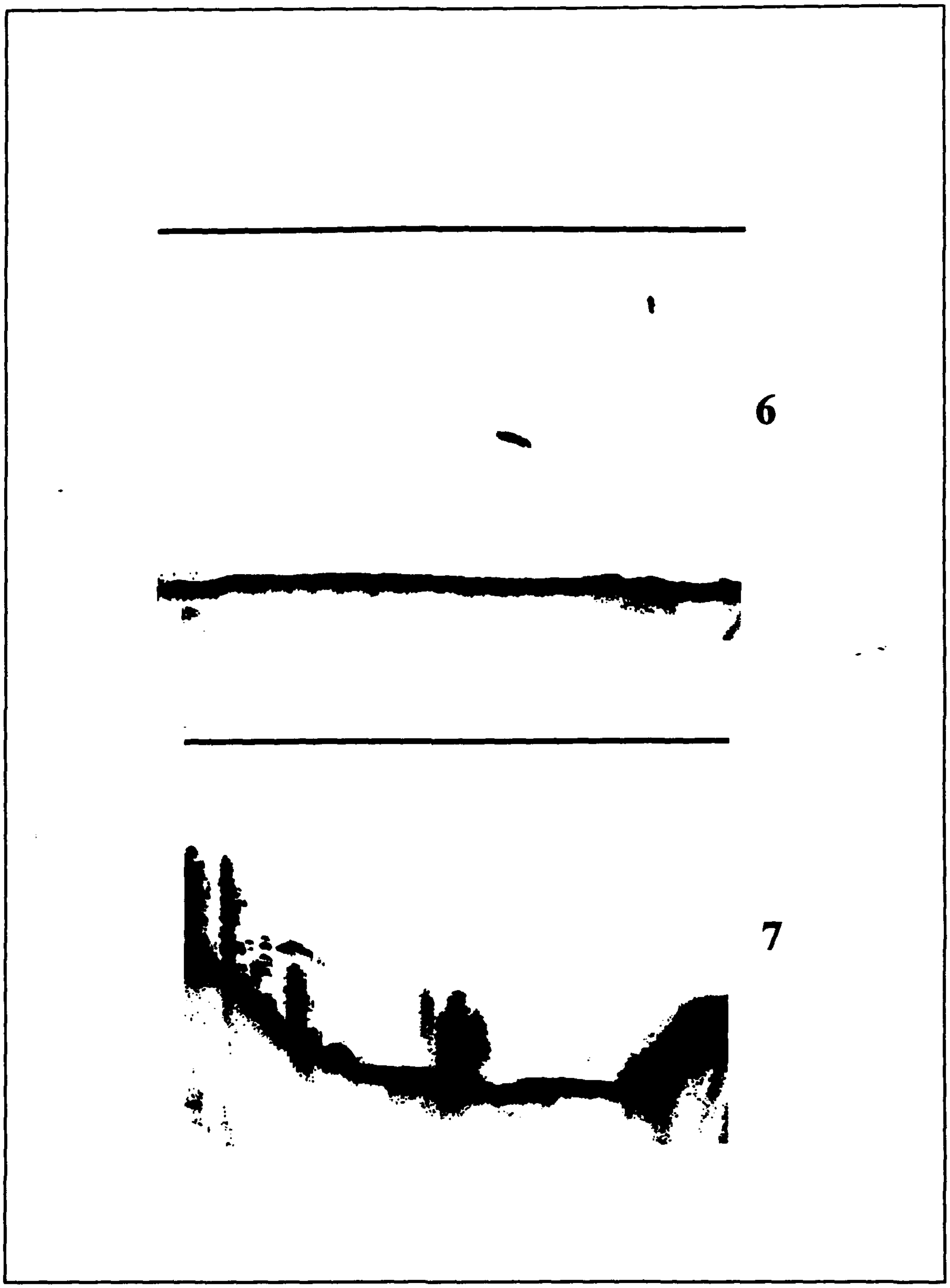

Figure A4. (Sheet 3 of 3)

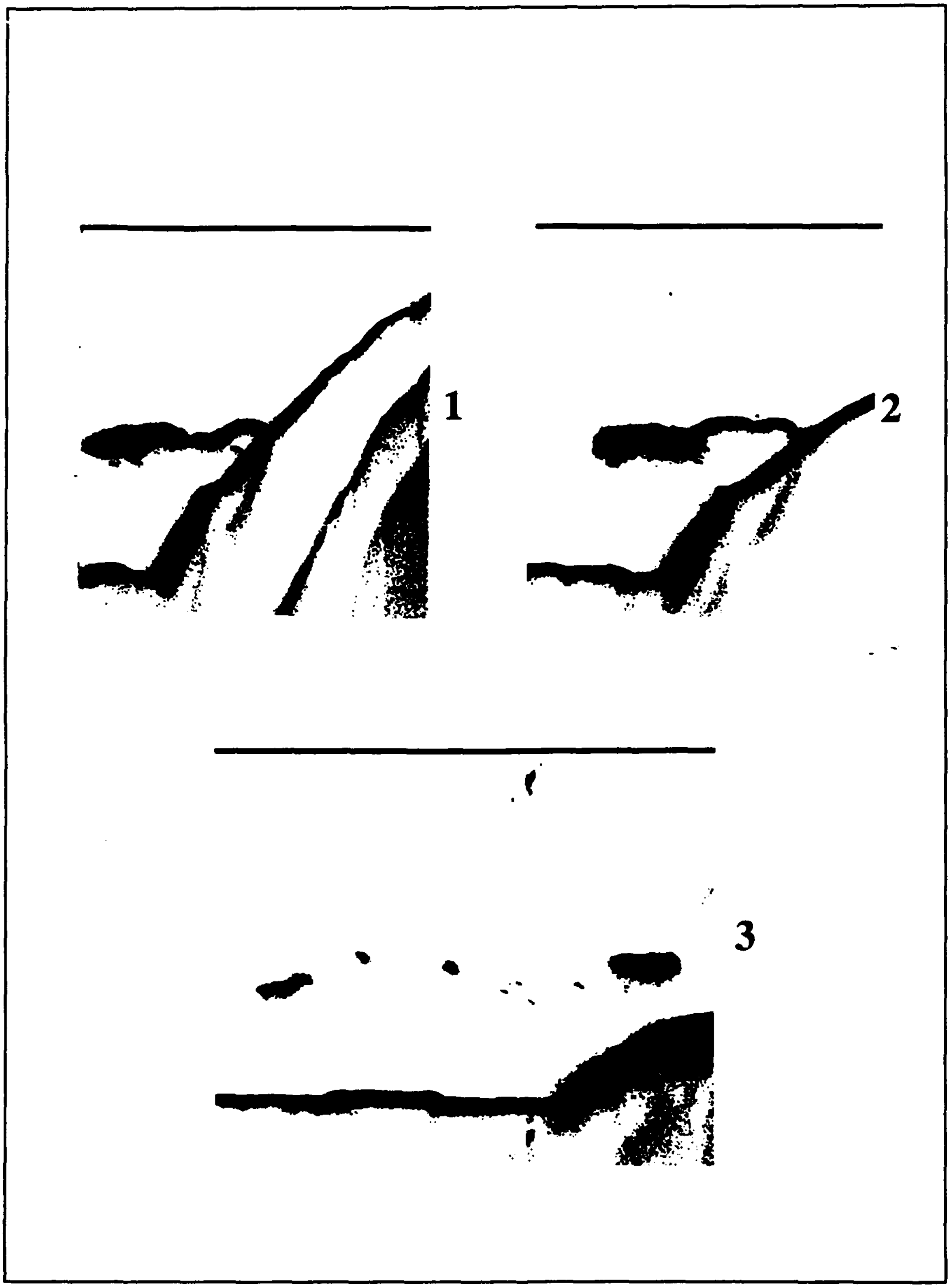

Figure A5. Hartwell Dam forebay, 4 Sep 90, 1744 hr (buoy line on left; face of dam on right) (Sheet 1 of 3)

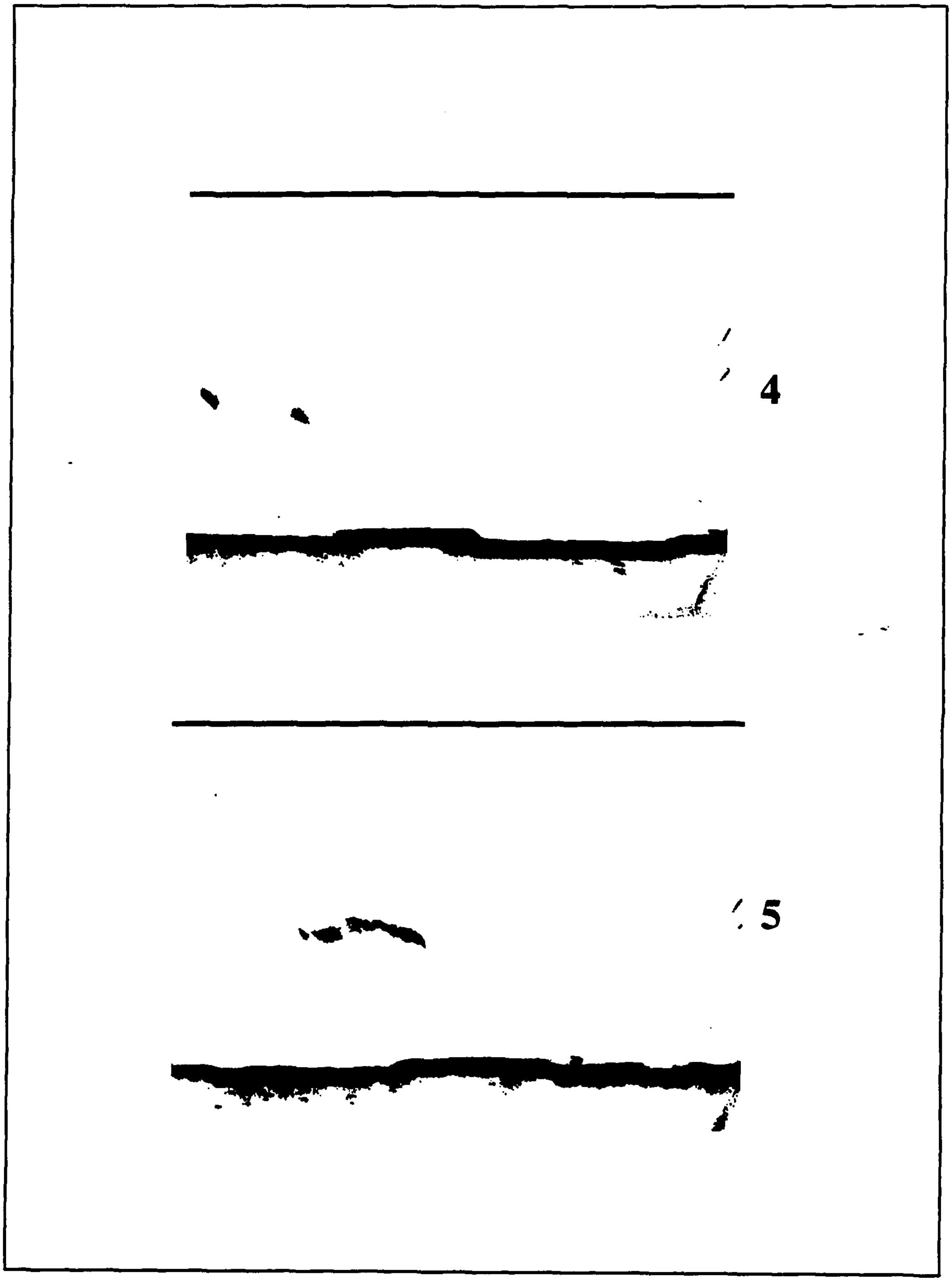

Figure A5. (Sheet 2 of 3)

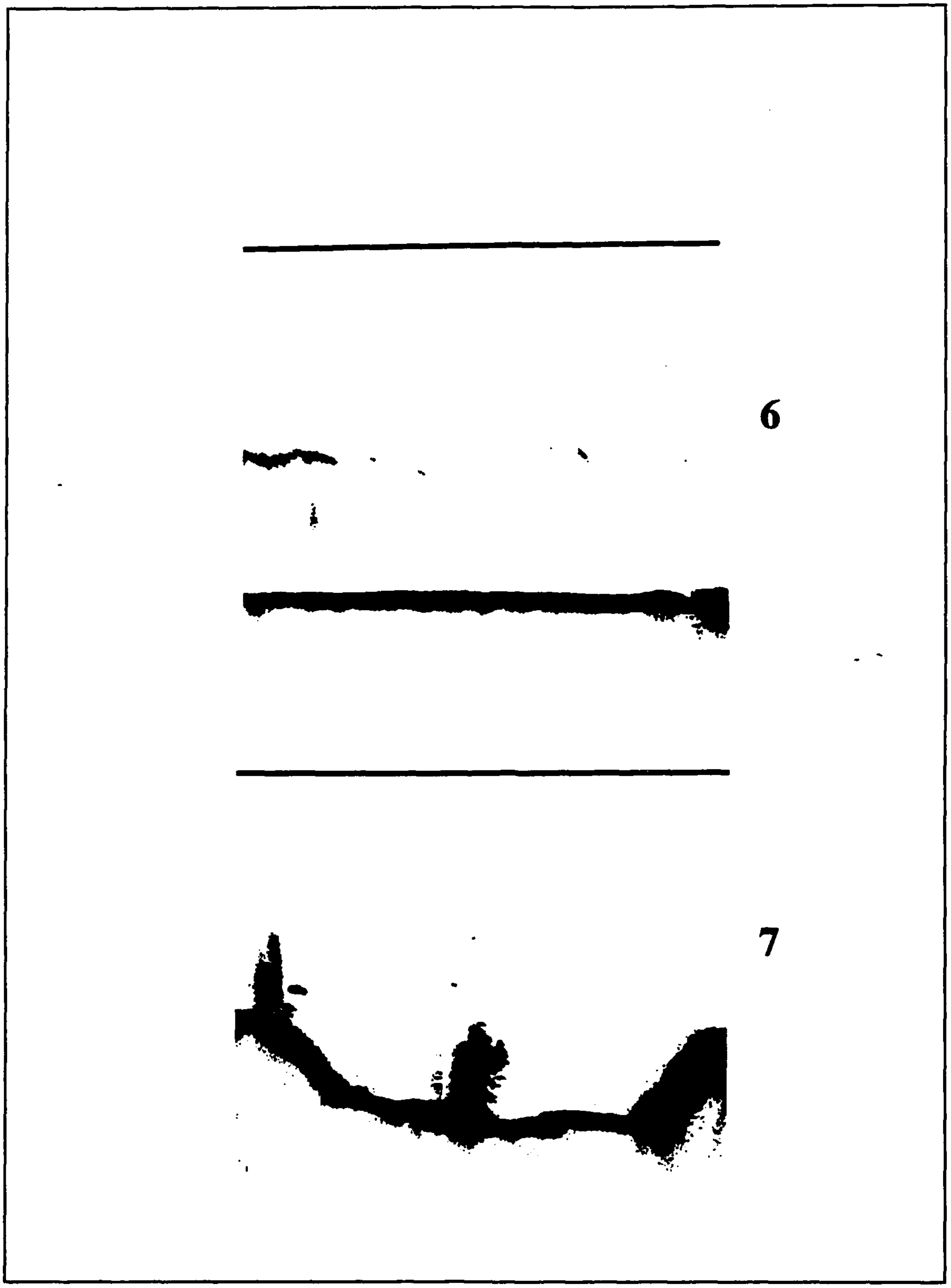

Figure A5. (Sheet 3 of 3)

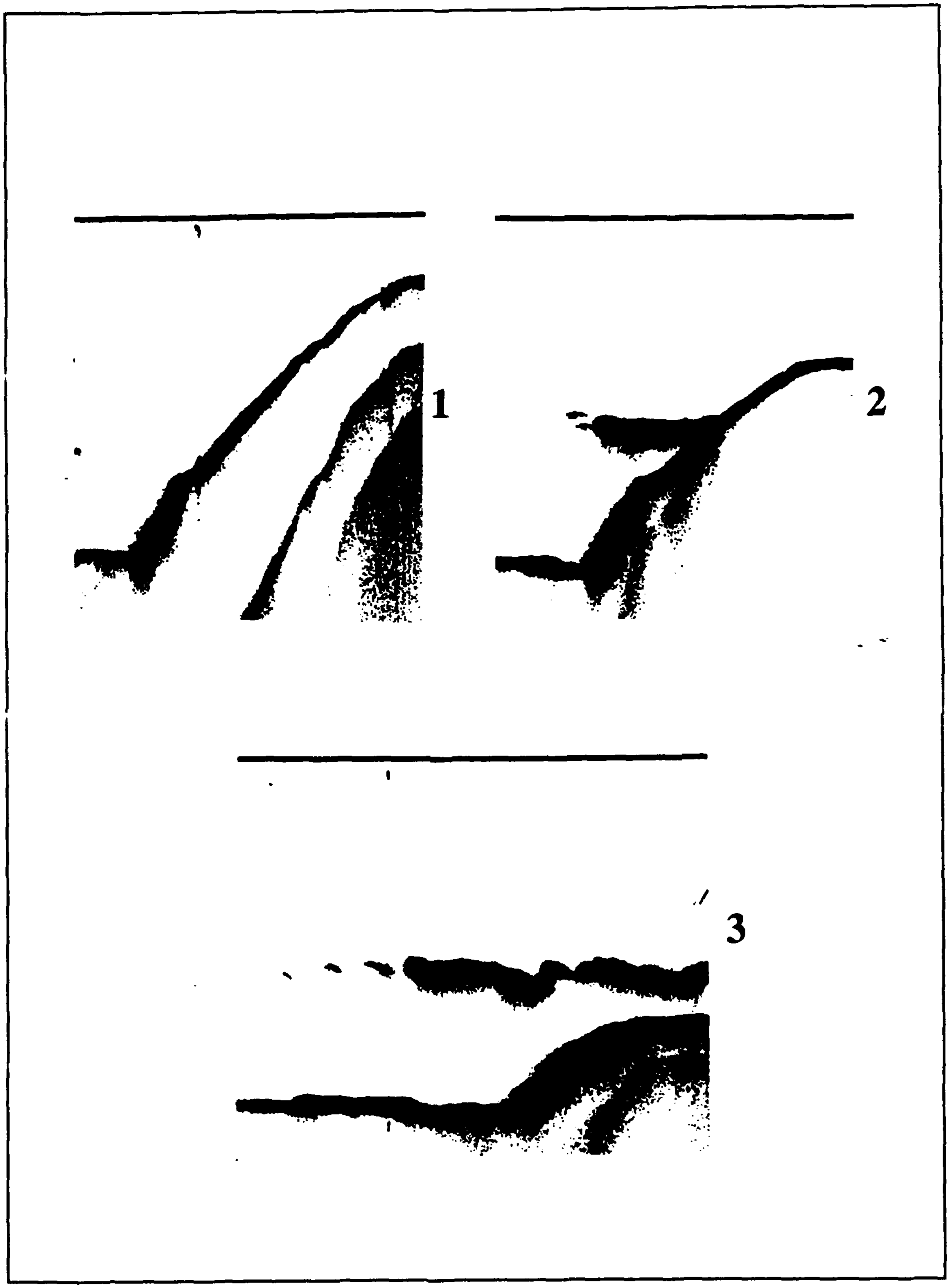

Figure A6. Hartwell Dam forebay, 4 Sep 90, 1830 hr (buoy line on left; face of dam on right) (Sheet 1 of 3)

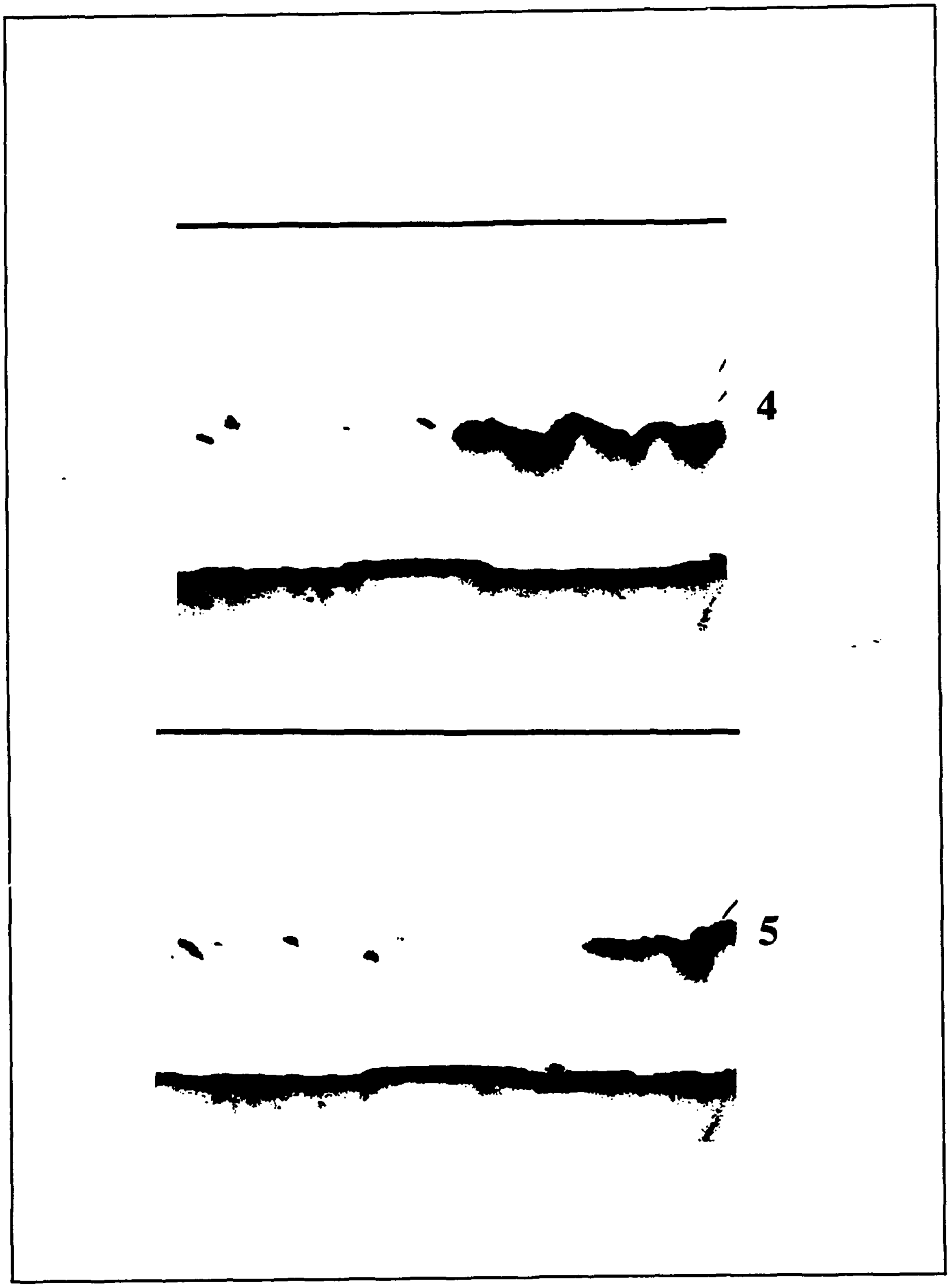

Figure A6. (Sheet 2 of 3)

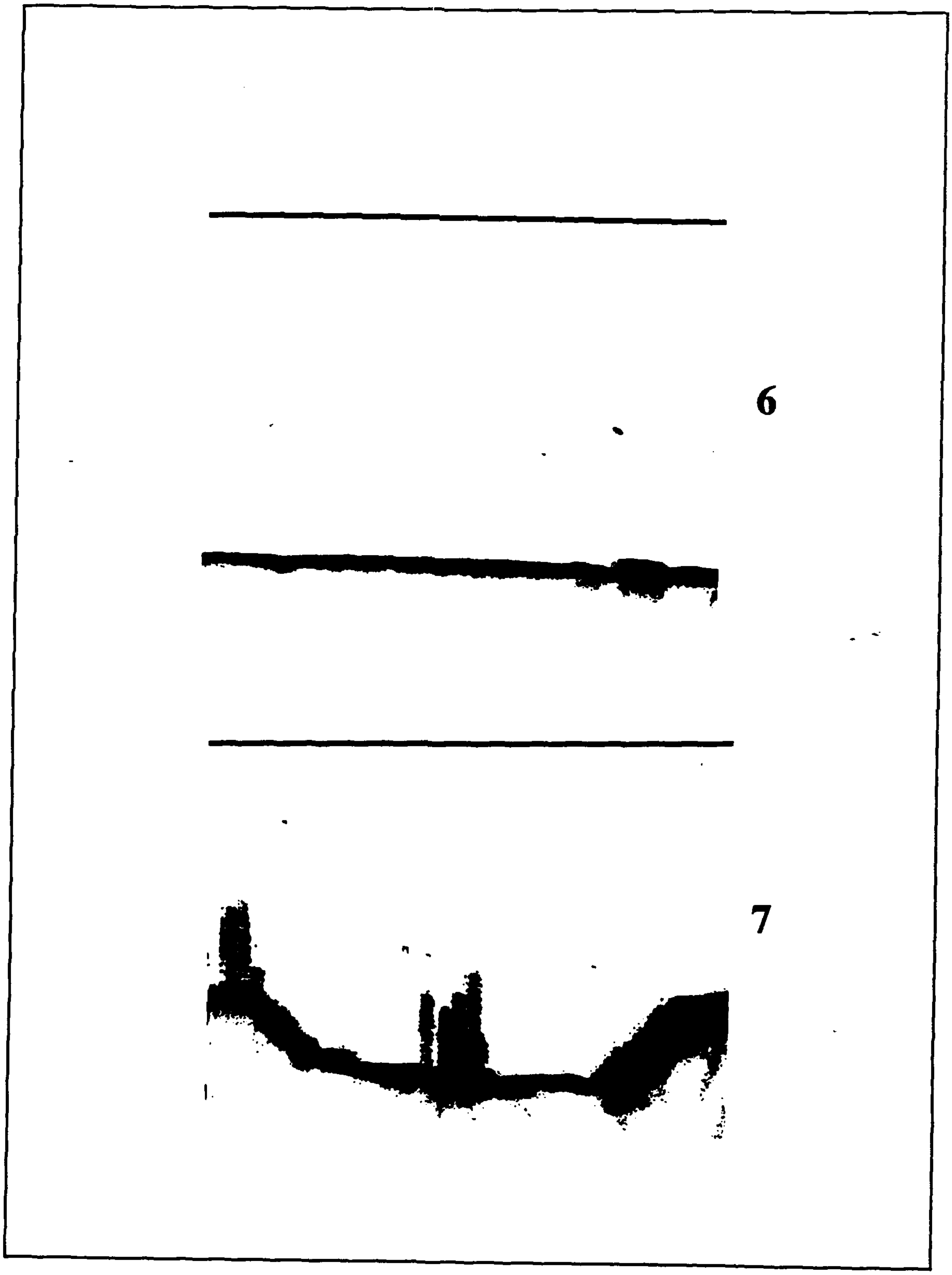

Figure A6. (Sheet 3 of 3)

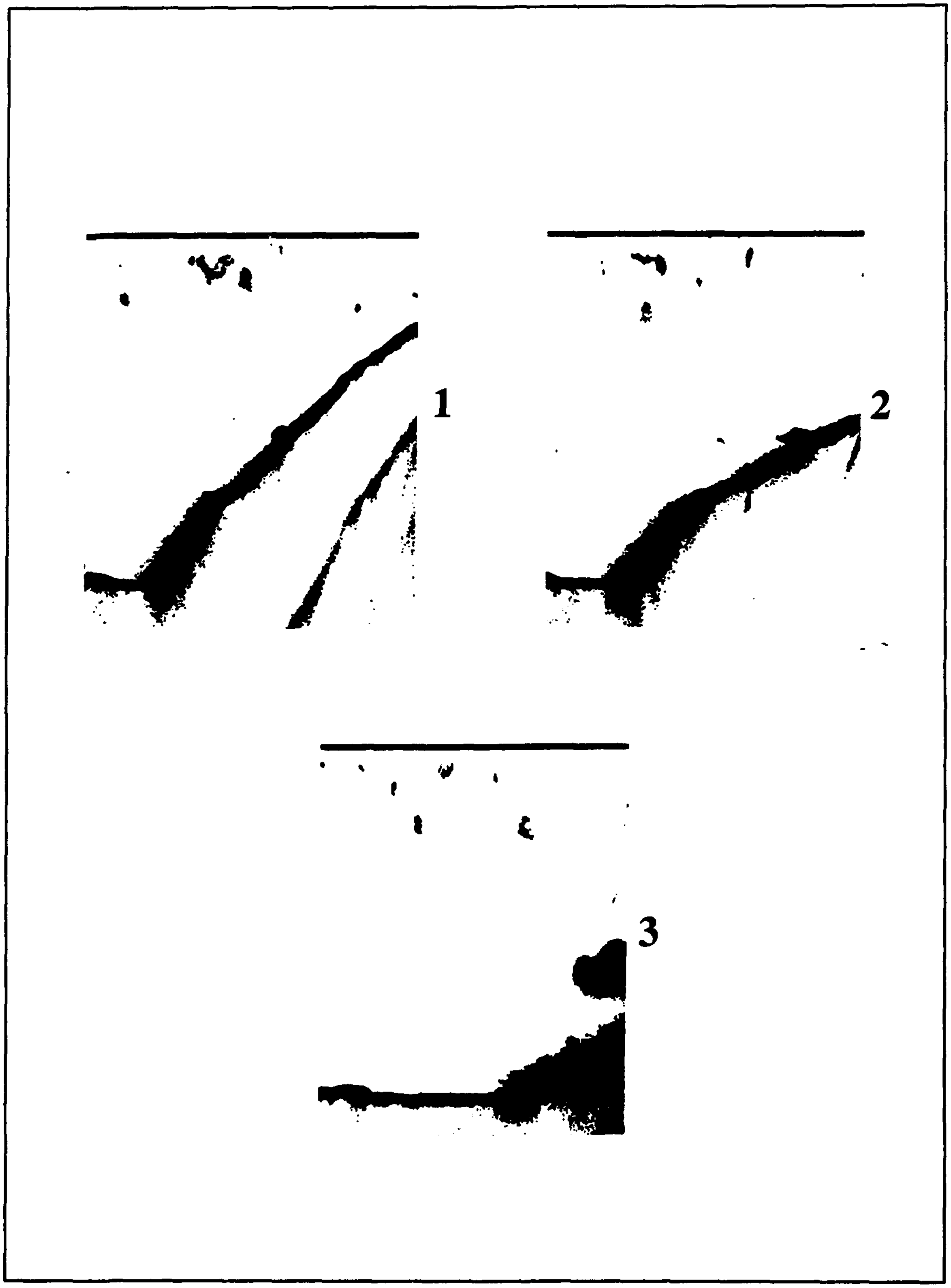

Figure A7. Hartwell Dam forebay, 5 Sep 90, 1049 hr (buoy line on left; face of dam on right) (Sheet 1 of 3)

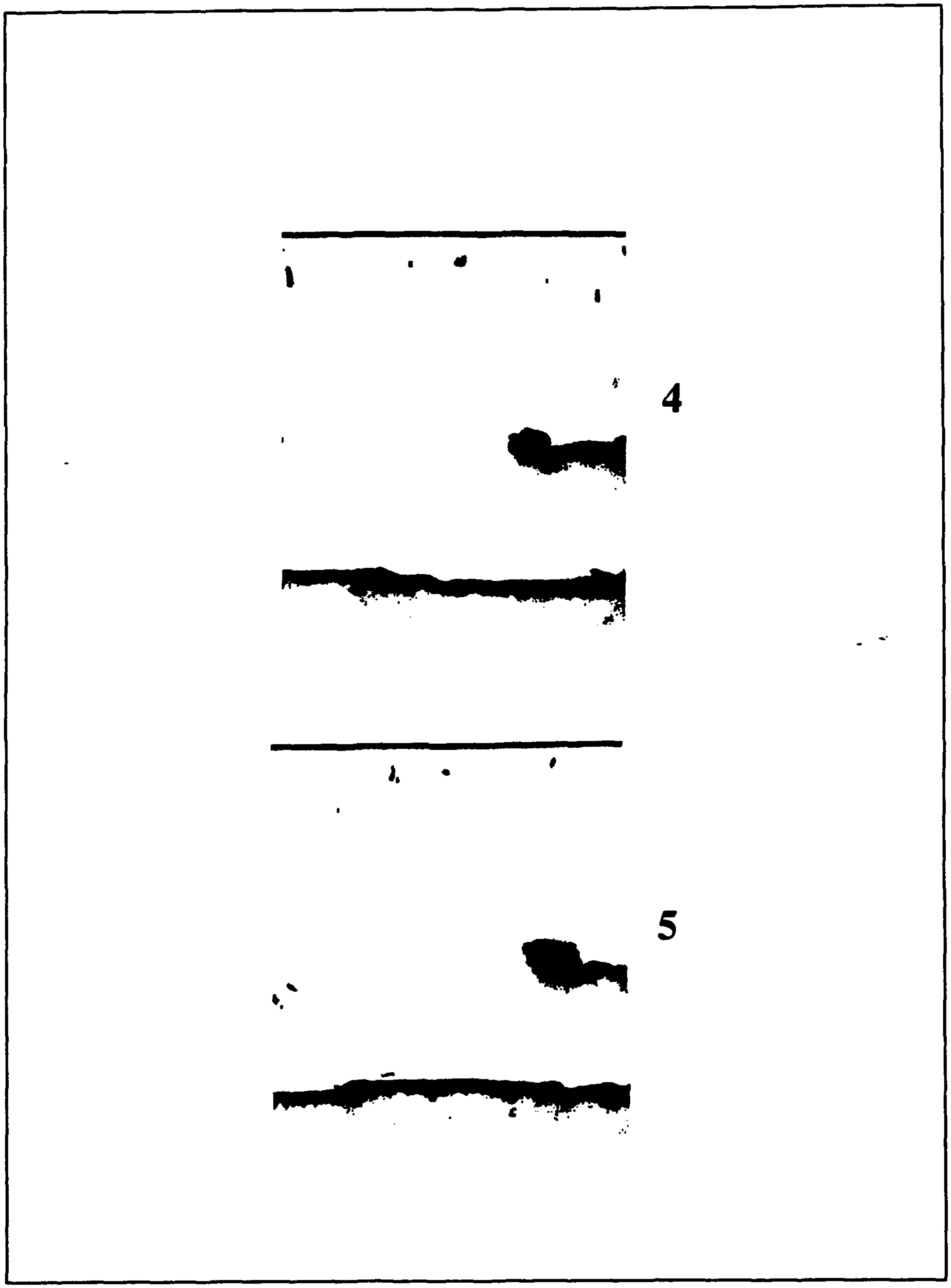

Figure A7. (Sheet 2 of 3)

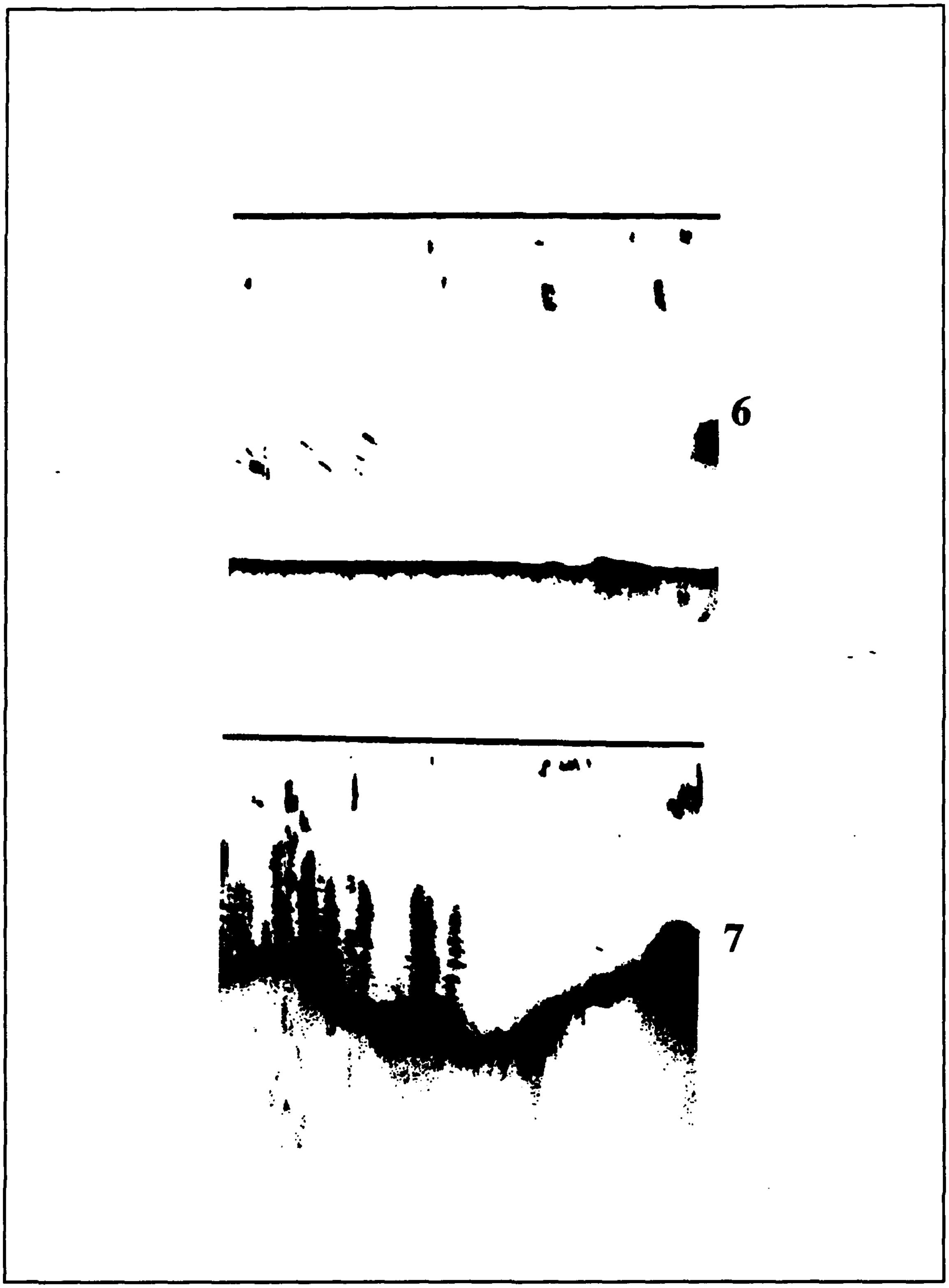

Figure A7. (Sheet 3 of 3)

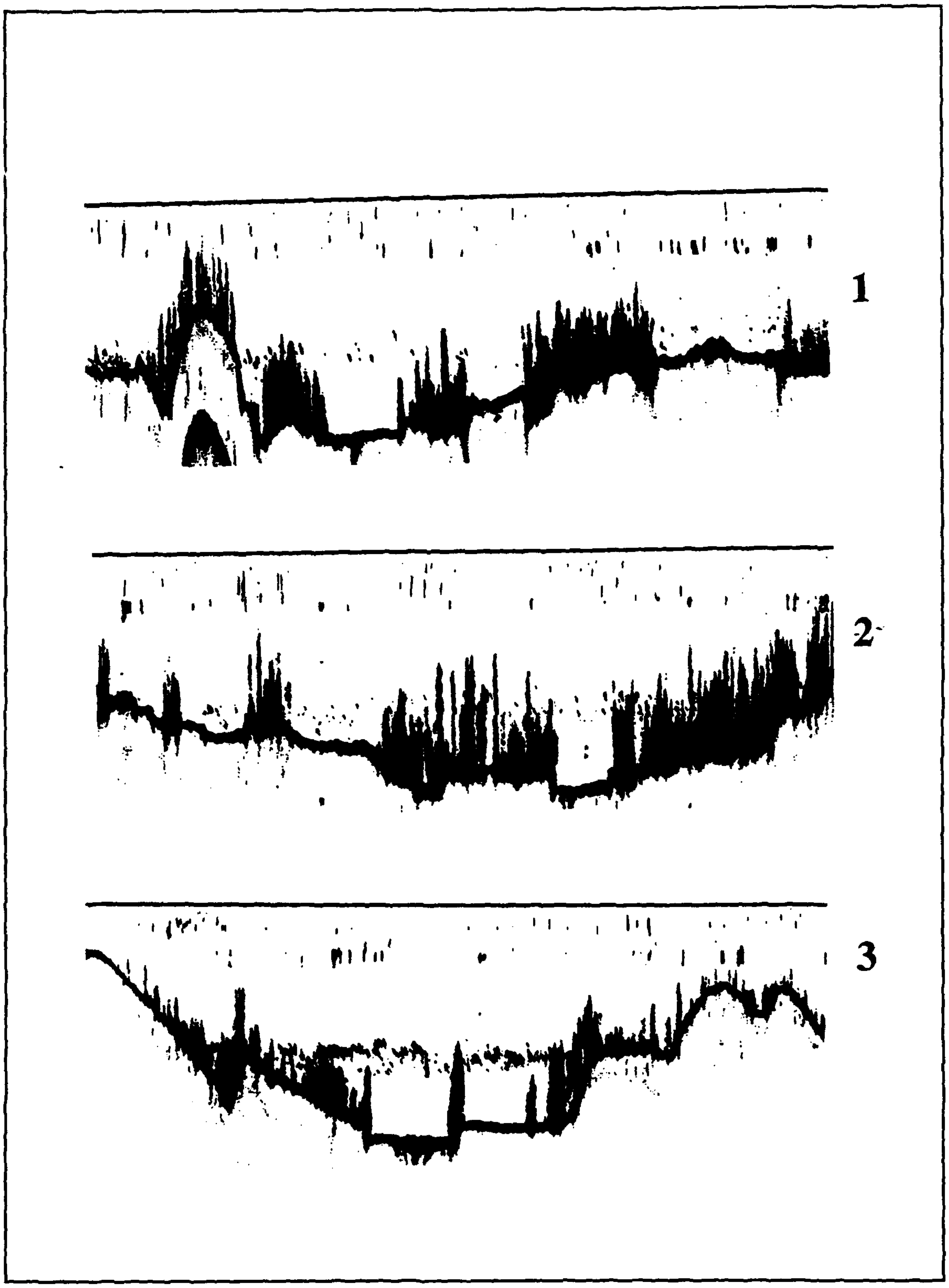

Figure A8. Hartwell Reservoir, 5 Sep 90 (Sheet 1 of 3)

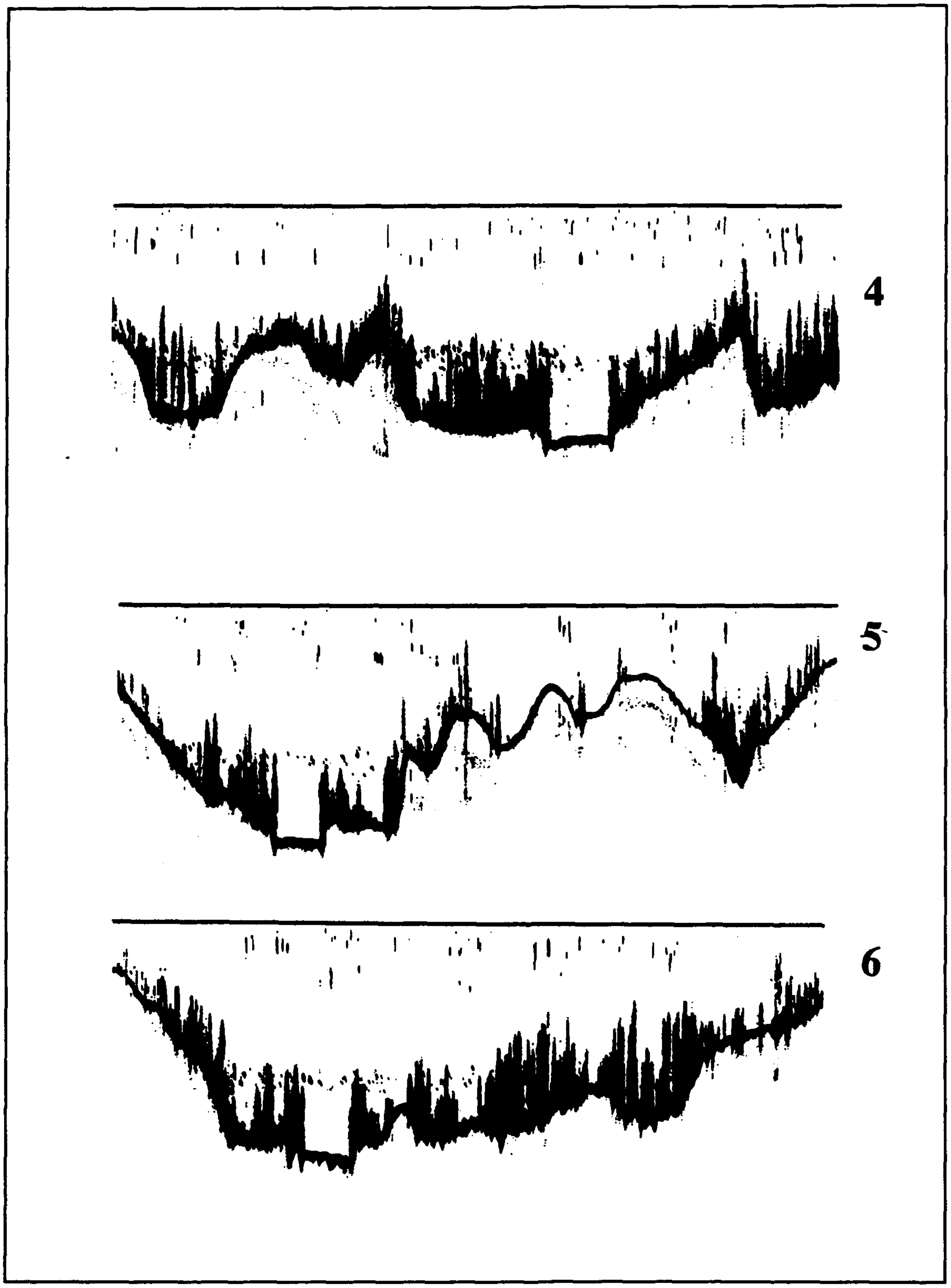

Figure A8. (Sheet 2 of 3)

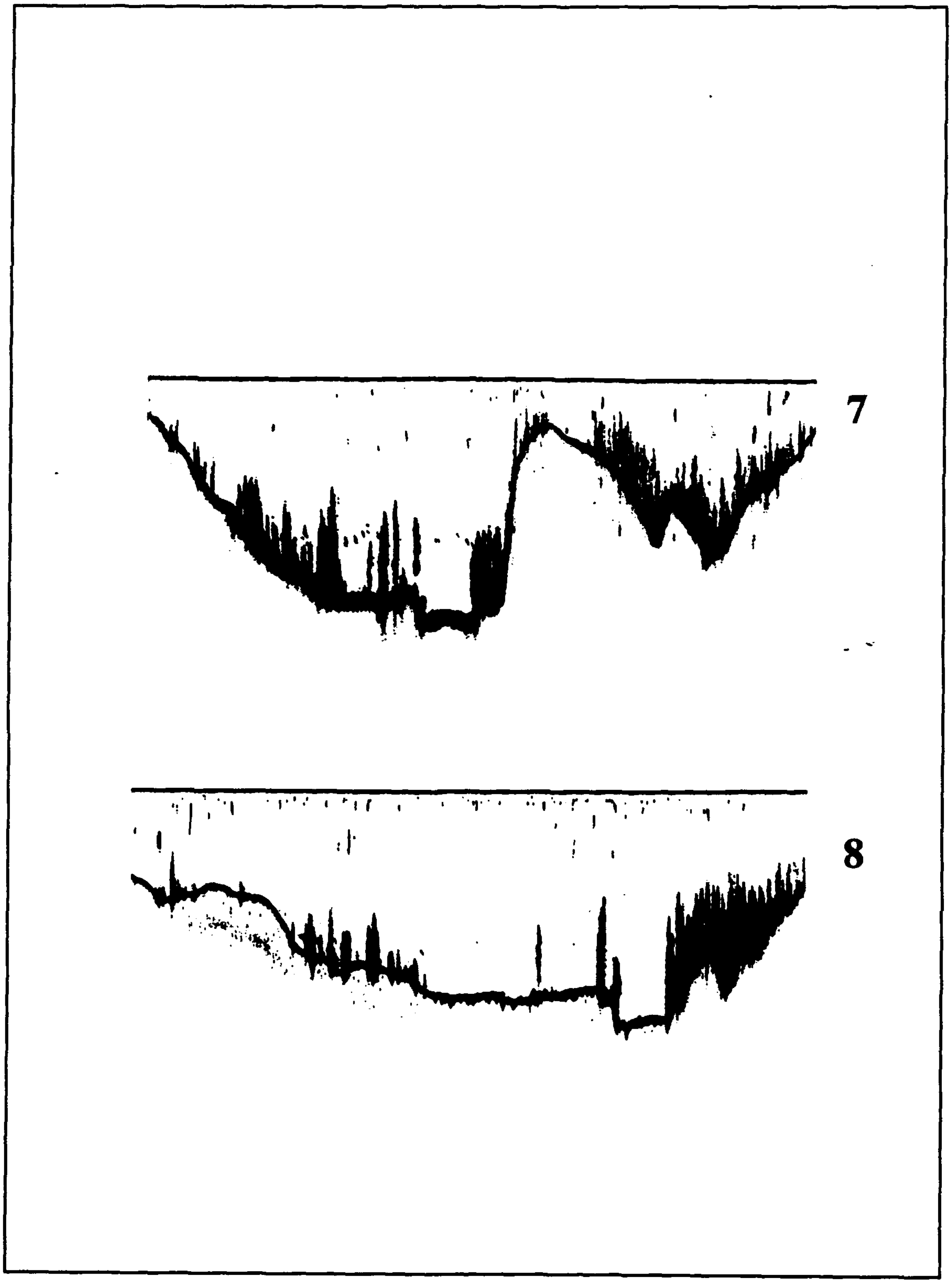

Figure A8. (Sheet 3 of 3)